Higgs Inv @ 100 TeV

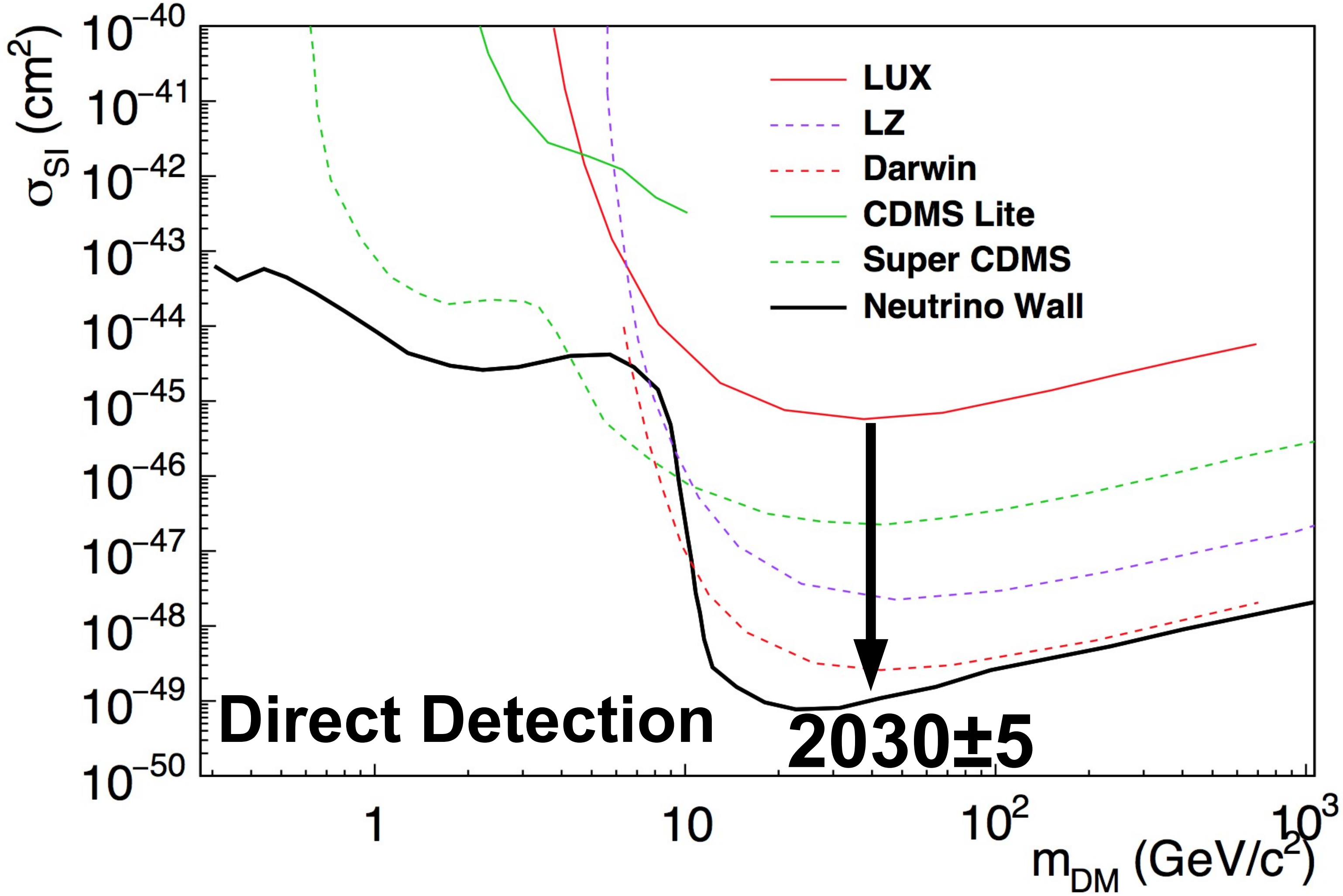
Phil Harris (MIT)
w/help from
K.Hahn(NWU) & MLM (CERN)

This talk

- This talk will review do some archeology
  - Word is there is some confusion about these results
  - These slides are 90% from an old talk in 2018
    - https://indico.cern.ch/event/618254/timetable/
  - No studies have been done subsequently
    - Text is here : https://inspirehep.net/literature/1749109
- Present Higgs invisible for 100 TeV benchmark
  - Review of LHC projections
- Potential to update these studies if needed
  - This work is closely tied to the CMS monojet analysis

Dark Matter searches not @ collider

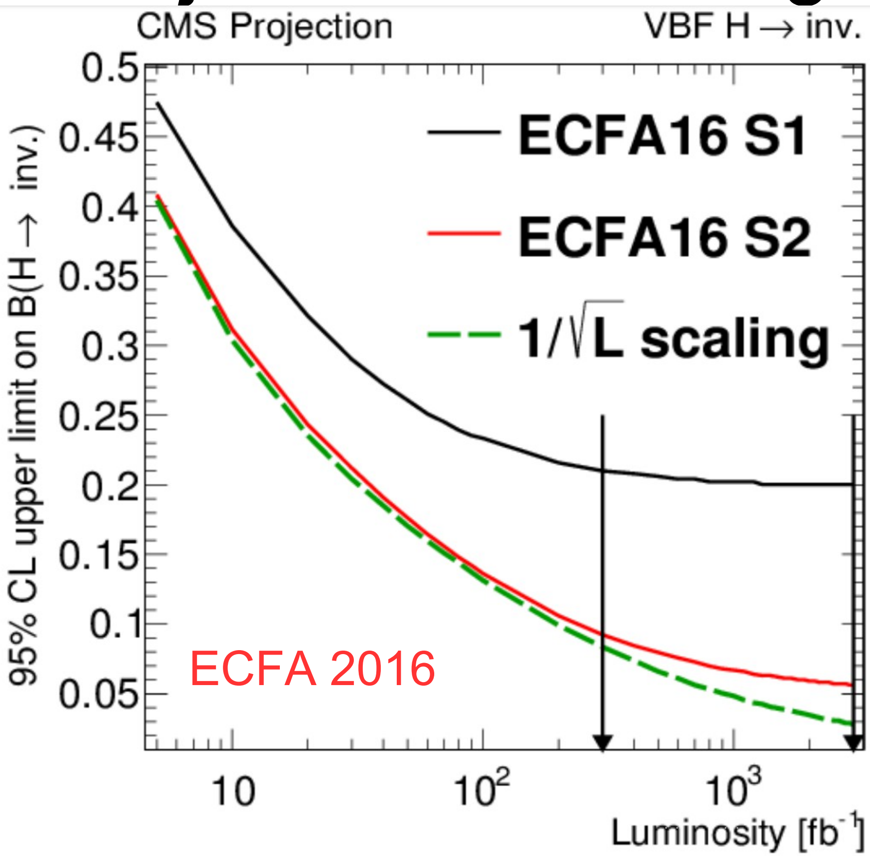
Dark matter searches not at colliders have clear benchmarks

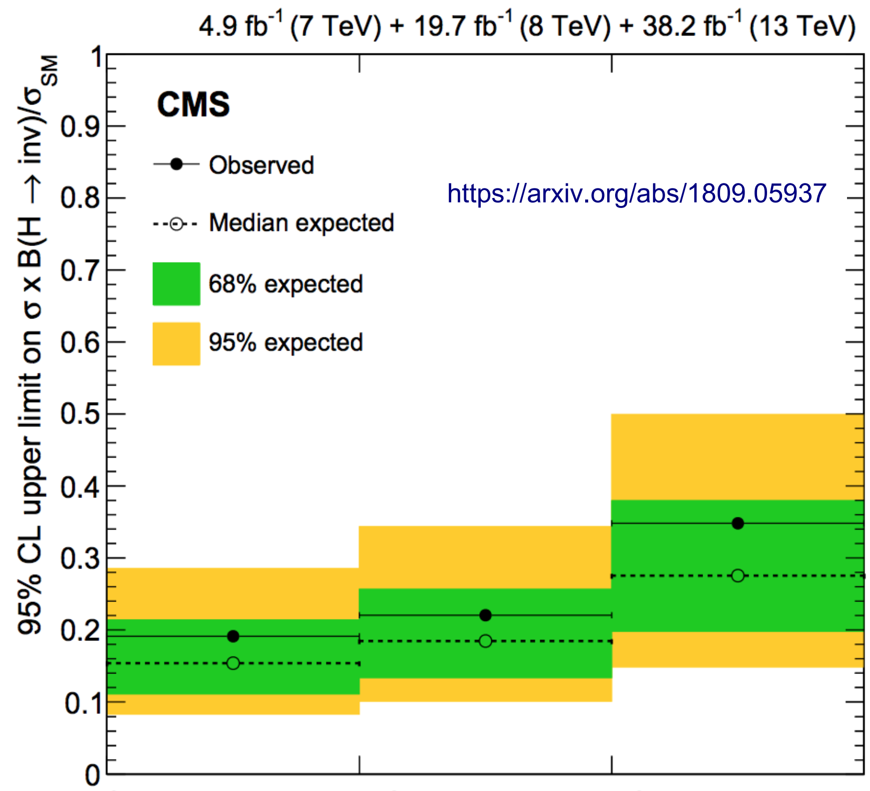


Goal: get to the Neutrino background wall

Full Scaling expected Scaling

- Projections at LHC go to <3%

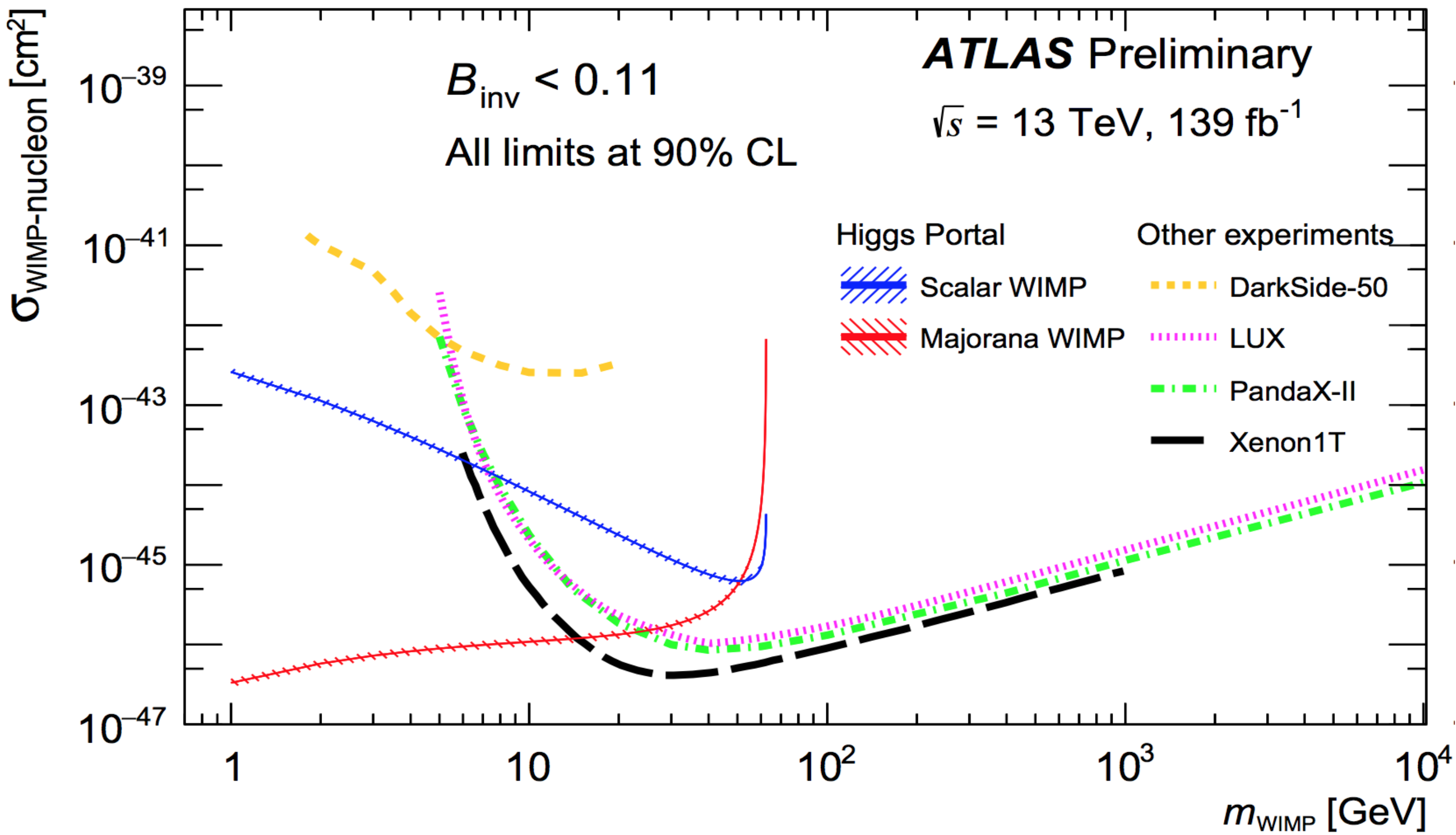




	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
$300\ fb^{-1}$	0.210	0.092	0.084
$3000\ fb^{-1}$	0.200	0.056	0.028

Current Higgs Invisible Search

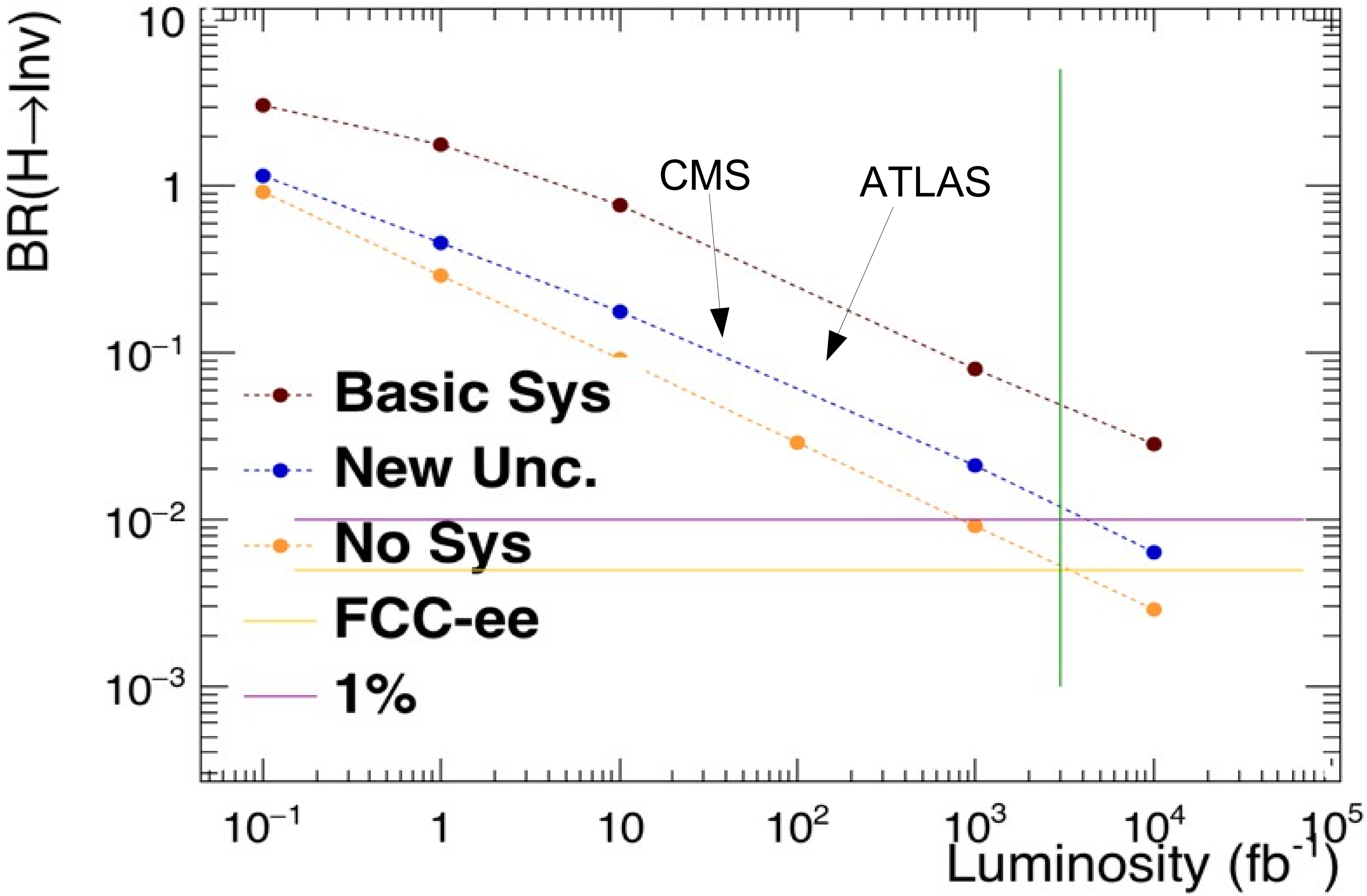
- This model is the same as Higgs invisible search



Expected 95%:
BR(H→Inv) < 14% (CMS combined 35fb^{-1})
BR(H→Inv) 13% (ATLAS VBF 139fb^{-1})

Projections

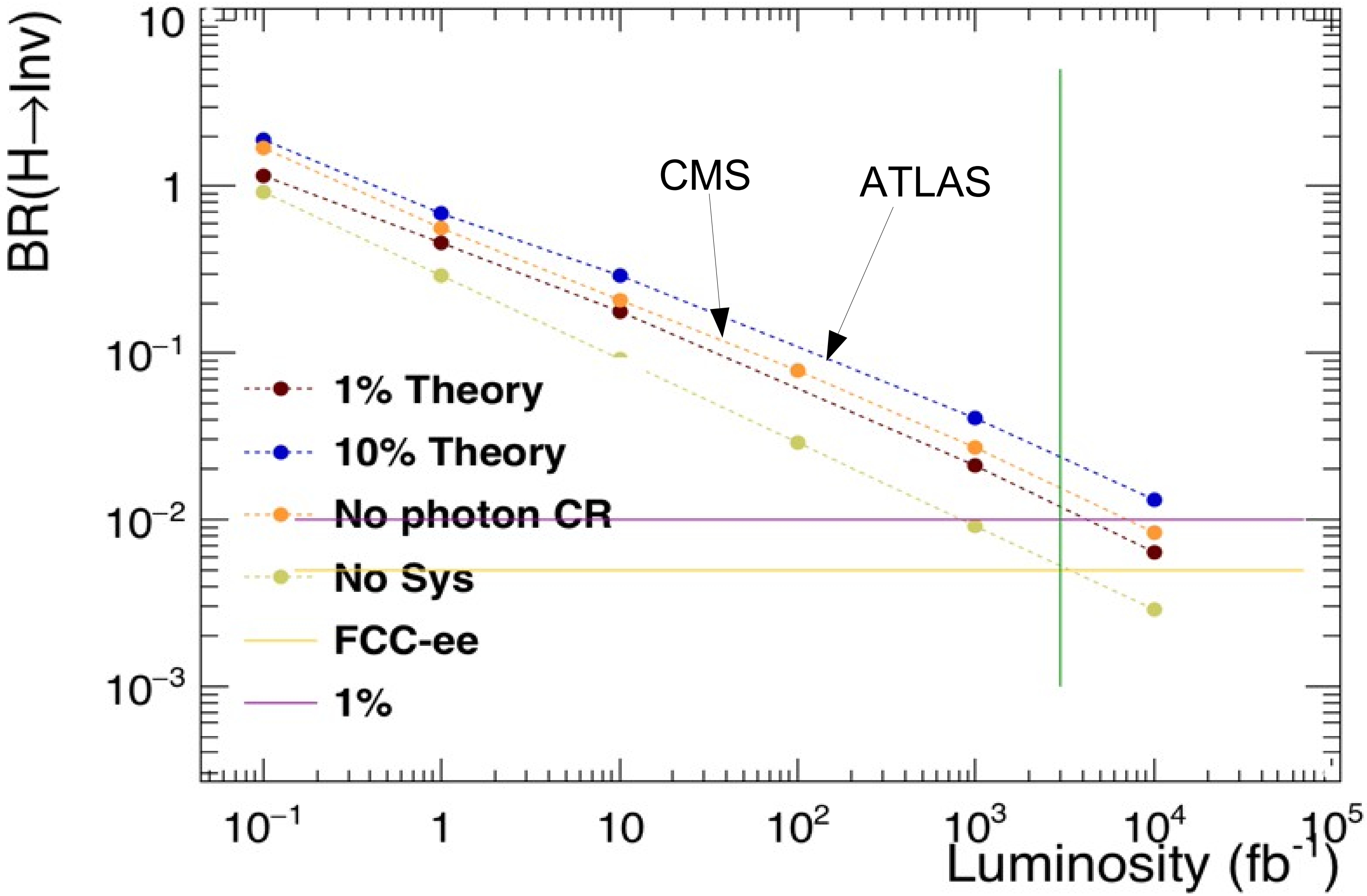
- Higgs Invisible propagated through



Hit 1% with the full unc. Scheme and 3 ab^{-1}

Alternative unc. Scheme's

- Previous best projections were like blue line



1% we are assuming NNLO+EWK for VBF topology

Summary Benchmarks for FCC

- Higgs invisible (explicitly) :
  - LHC will reach roughly 1% barrier
  - Aim to probe couplings at 10^{-2} (compete with DD)

- These results translate to Scalar/Pseudoscalar
  - No fundamental difference with them

- In previous talks
  - Have shown for SM-like couplings @ 100 TeV can probe most/if not all allowed DM phase space
  - This talk attempts to give a feel of required sensitivity

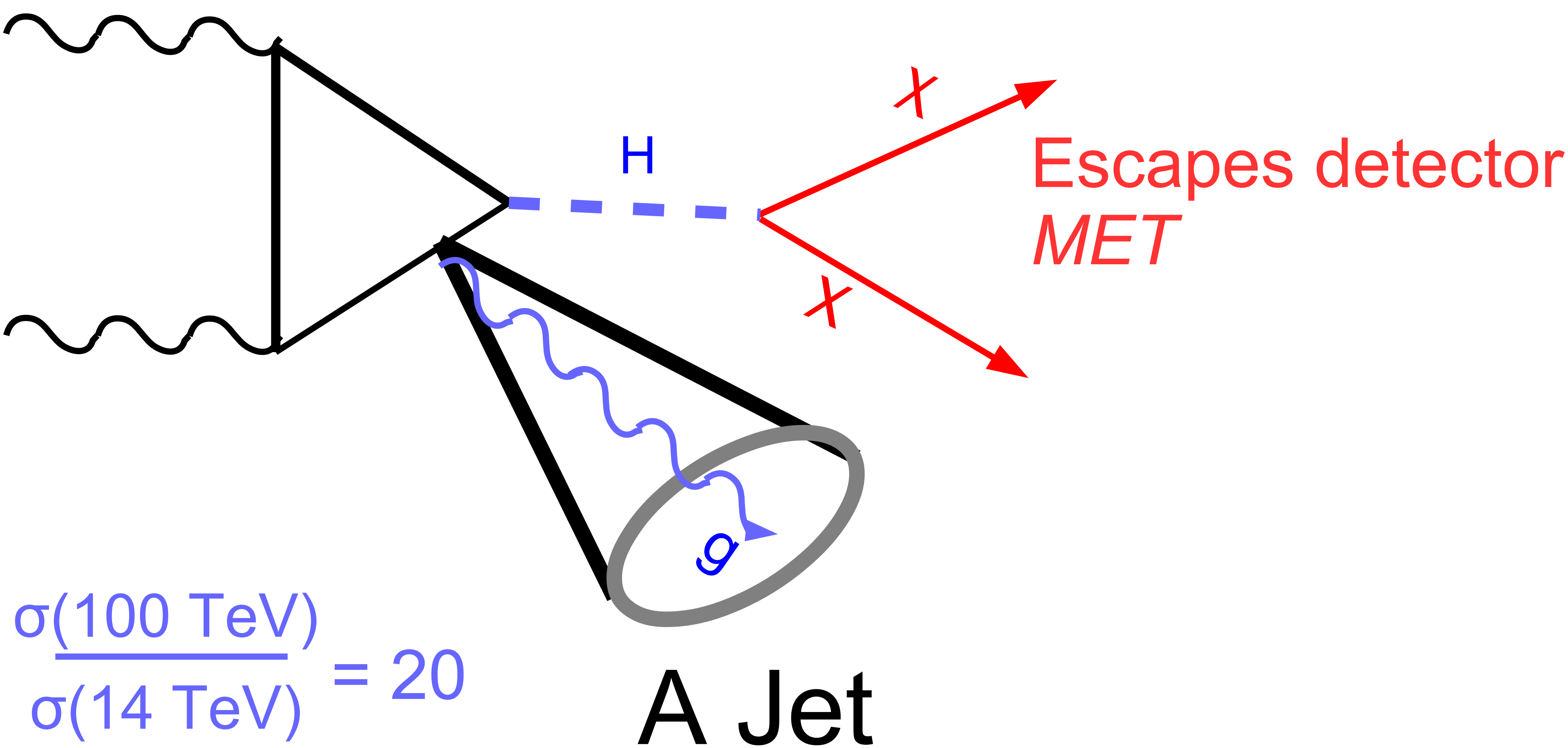
Using the Luminosity

FCC-hh as Higgs Production tool

- Rate of Higgs production at 100 TeV is very large
  - 800 Higgs events per pb
- Focus of this talk :
  - Whats our sensitivity to H→Inv?
- H→Inv probes a large variety of models
  - Benchmark for exotic Higgs sensitivity
  - Benchmark for low mass scalars
- Fundamental question:
  - What are the advantages of such high rates

The Basic Monojet Search

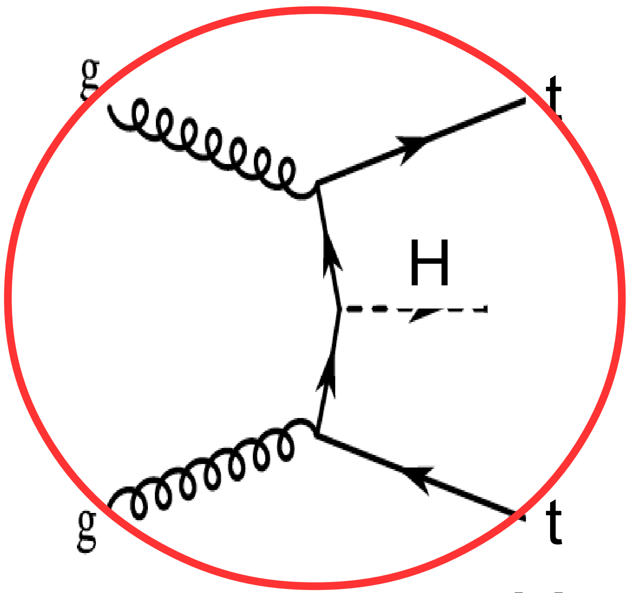
Escaping detector gives us signatures of *MET*

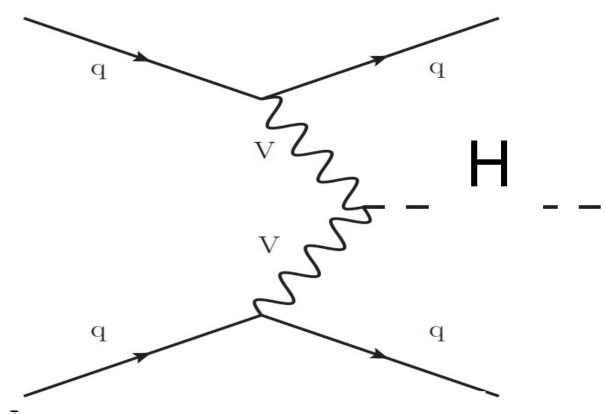


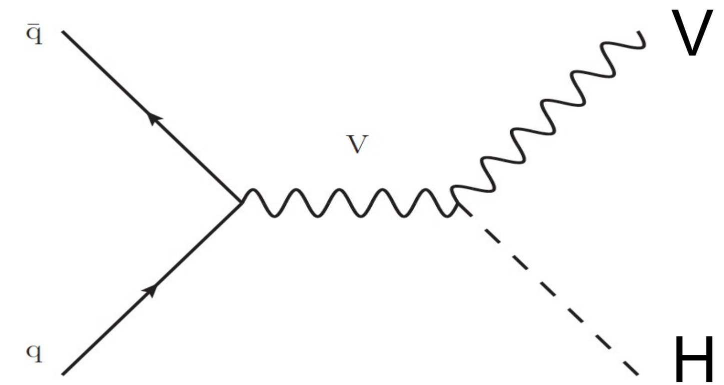
$$\frac{\sigma(100\ \text{TeV})}{\sigma(14\ \text{TeV})} = 20$$

Additional Probes

Higgs production has additional interesting signatures







	tt+H	VBF	VH
$\frac{\sigma(100\ \mathrm{TeV})}{\sigma(14\ \mathrm{TeV})}$	61	18	11

tt+H has a very distinct initial state

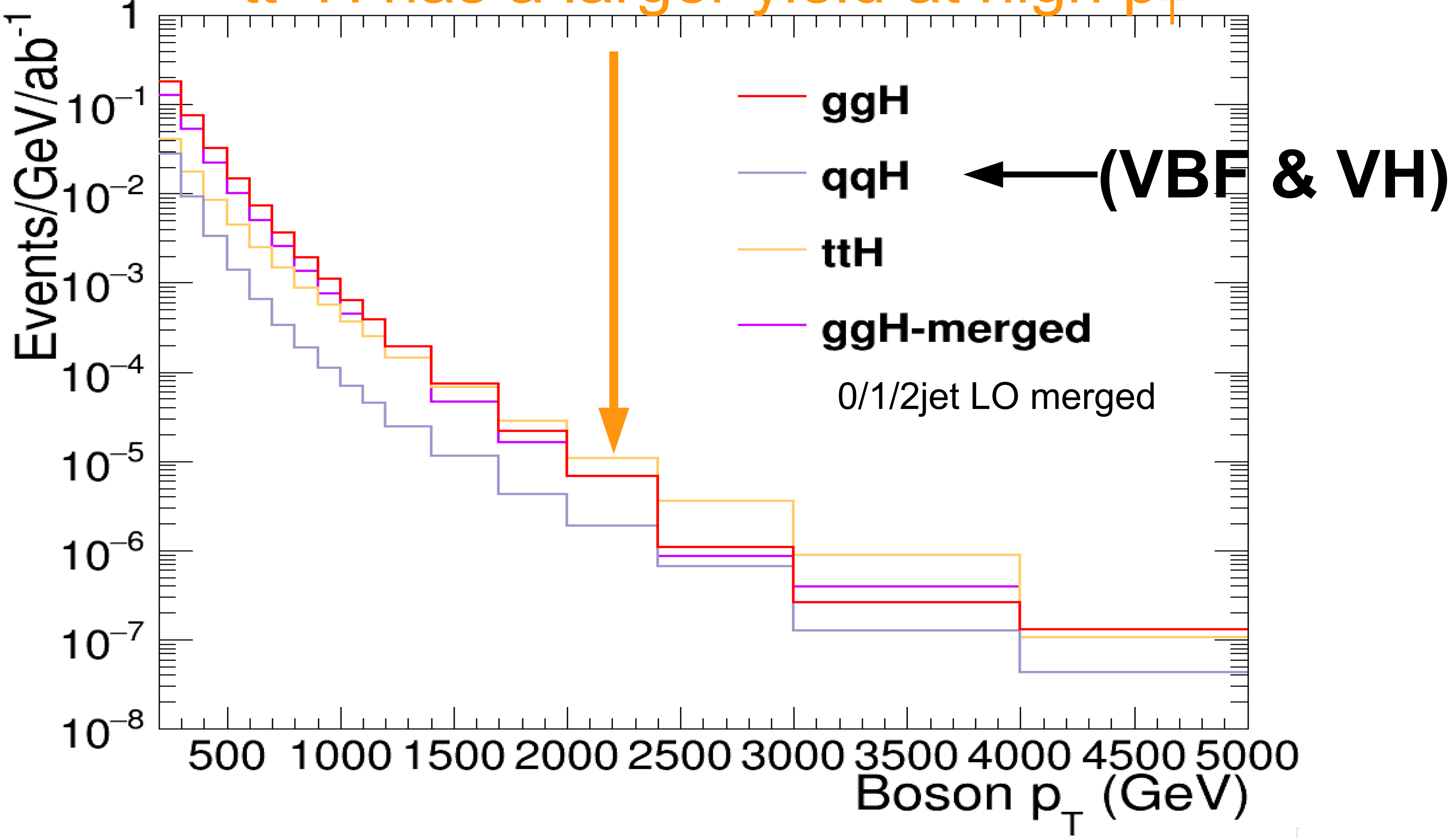
Large cross section increase makes :

tt+H→Invisible the golden invisible channel

Additional Observation

- A key feature at high p_T

tt+H has a larger yield at high p_T

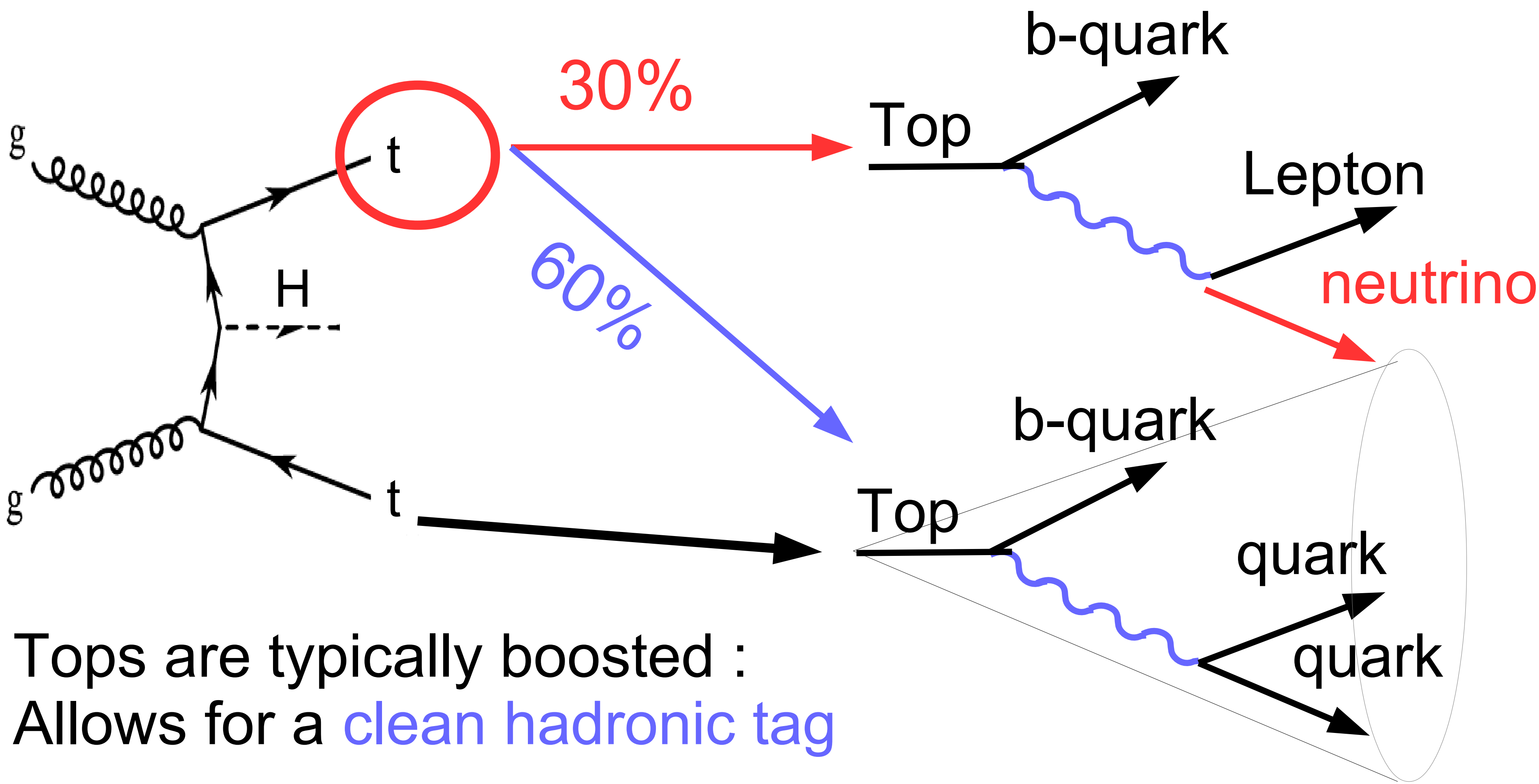


Inclusive ttH can be made relatively pure

Experimental Approach in H→Inv

- Use full simultaneous fit approach
- Delphes for simulation
  - In s-channel studies used toy smearing
- Weighted MC generation (makes things fast)
  - This was not done s-channel studies
- Same experimental setup otherwise as s-channel
  - Define control regions with leptons out to $|\eta| < 4.0$
  - Apply vetos based on this detector range
  - Approximate same lepton veto rates as LHC
    - Following CMS numbers (ATLAS is similar)
  - Skipped QCD background (its small in the end)

Designing the tt+H Analysis



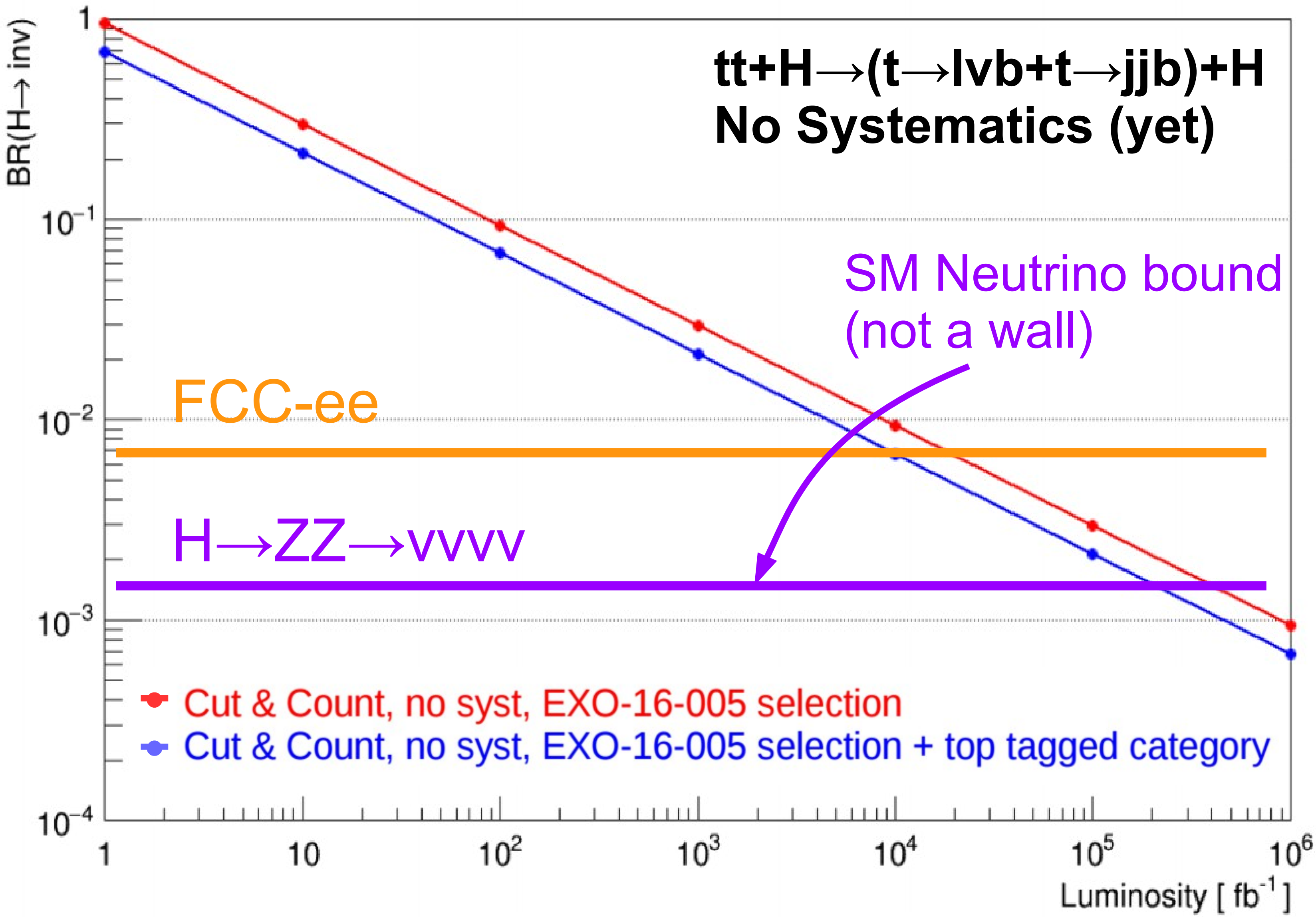
Tops are typically boosted :
Allows for a clean hadronic tag

With leptonic decay can get higher purity

Here:
consider lepton w/another hadronic top jet

Implications with a Pure category

Currently considering semi-leptonic channel without systematics

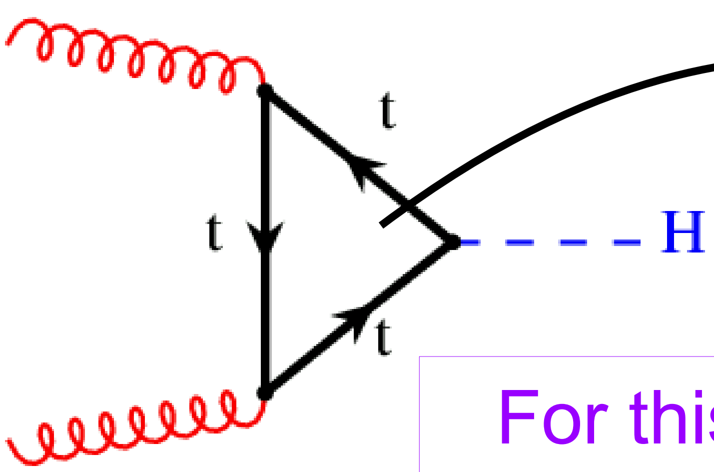


Crosses both FCC bounds and SM H Invisible bound

Monojet search
Straddling SM and BSM

Monojet(s) analysis

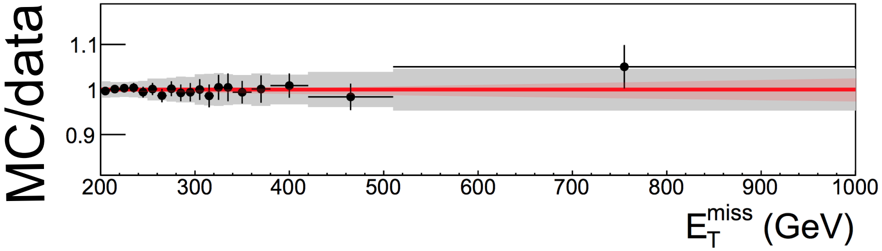
- Consider an analysis :
  - Veto leptons for $|\eta| < 4.0$
  - Fit the MET spectrum
    - Predict the MET spectrum with the highest level of precision
- In MET tail S/B is 2-5%
  - Aim to just exploit low purity with very large yields



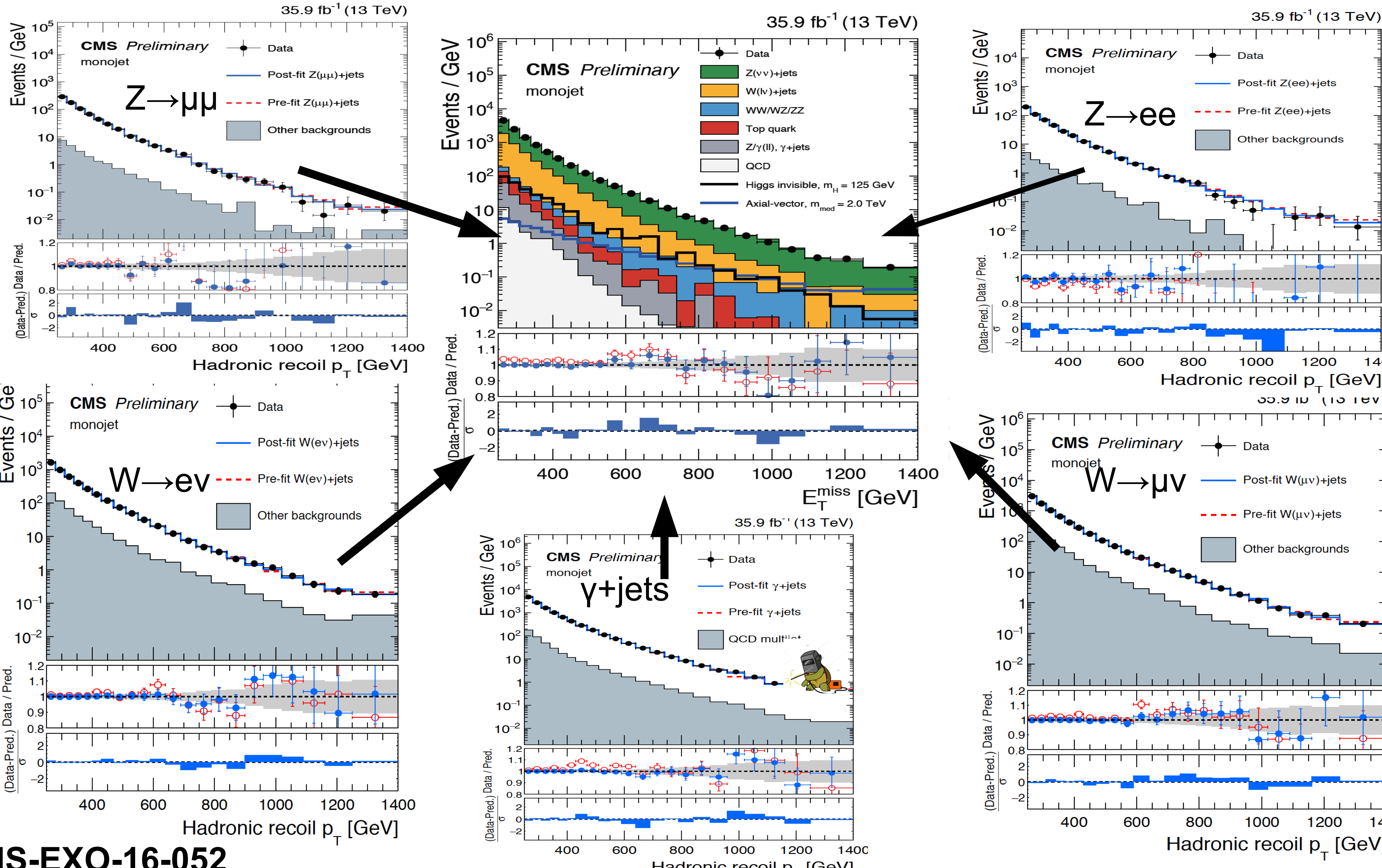
Finite top quark mass contribution crucial

Approximately known to NLO

For this study we have upgraded to Delphes FCC tune



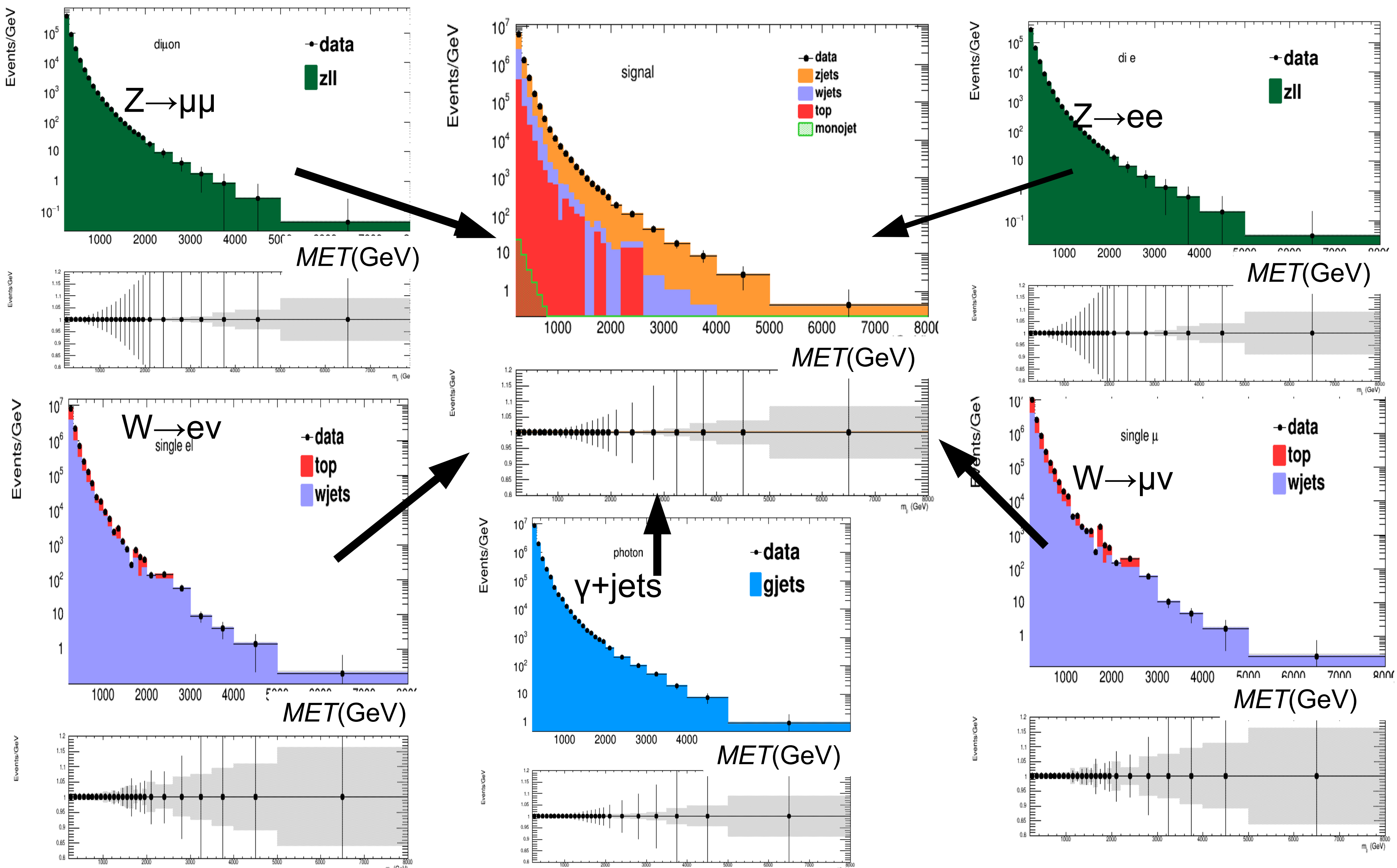
5 Control regions
15% uncertainty @ 1 TeV



CMS-EXO-16-052

Monojet analysis @ CMS

The same fitting scheme applies to 100 TeV (fits $1ab^{-1}$)

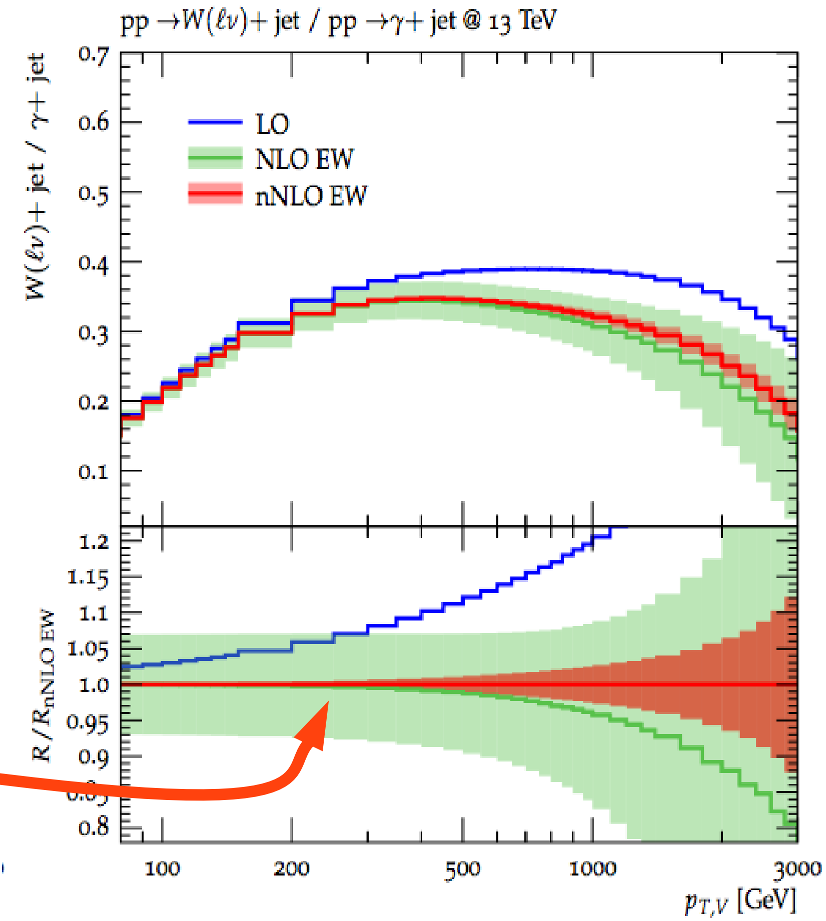


The foundation of this analysis

Going from γ or W → Z

Unc. → $\frac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T}$

- Key to this analysis ratios
  - Require best theoretical calculations
  - Current (N)NLO theoretical prescription brought additional ~40% on 36/fb analysis

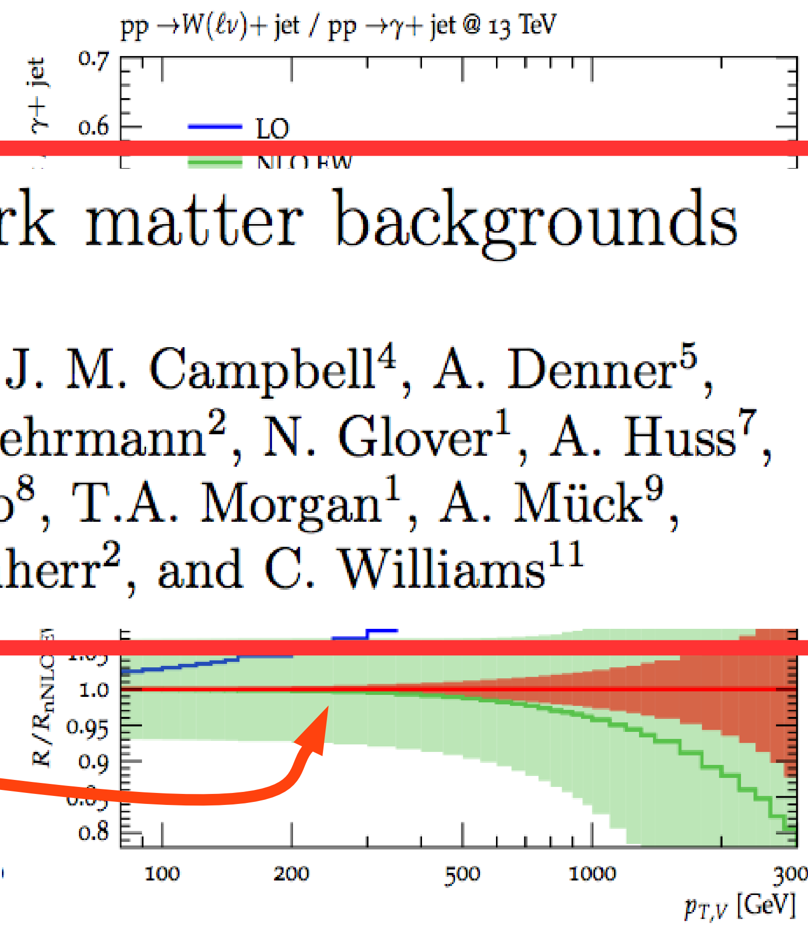


arxiv/1705.04664

The foundation of this analysis

Going from γ or W → Z

Unc. → $\dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$



Precise predictions for V+jets dark matter backgrounds

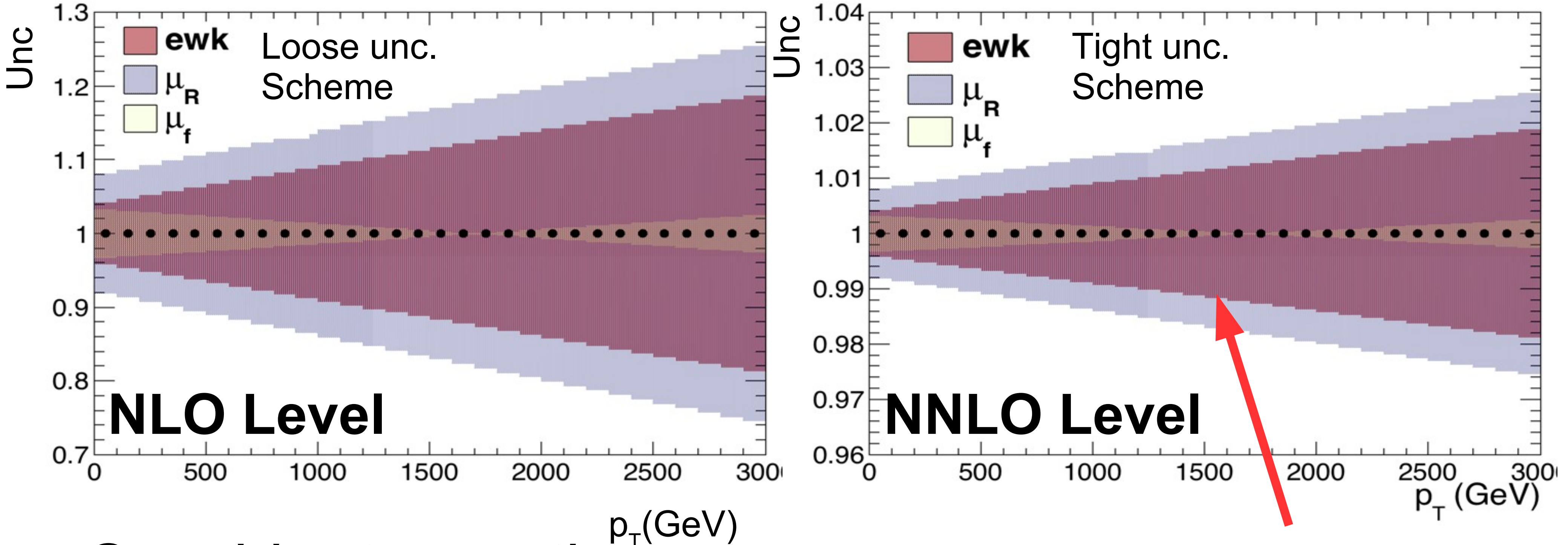
J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam*[8], M. Schönherr[2], and C. Williams[11]

prescription brought additional ~40% on 36/fb analysis

arxiv/1705.04664

Benchmarks for this study

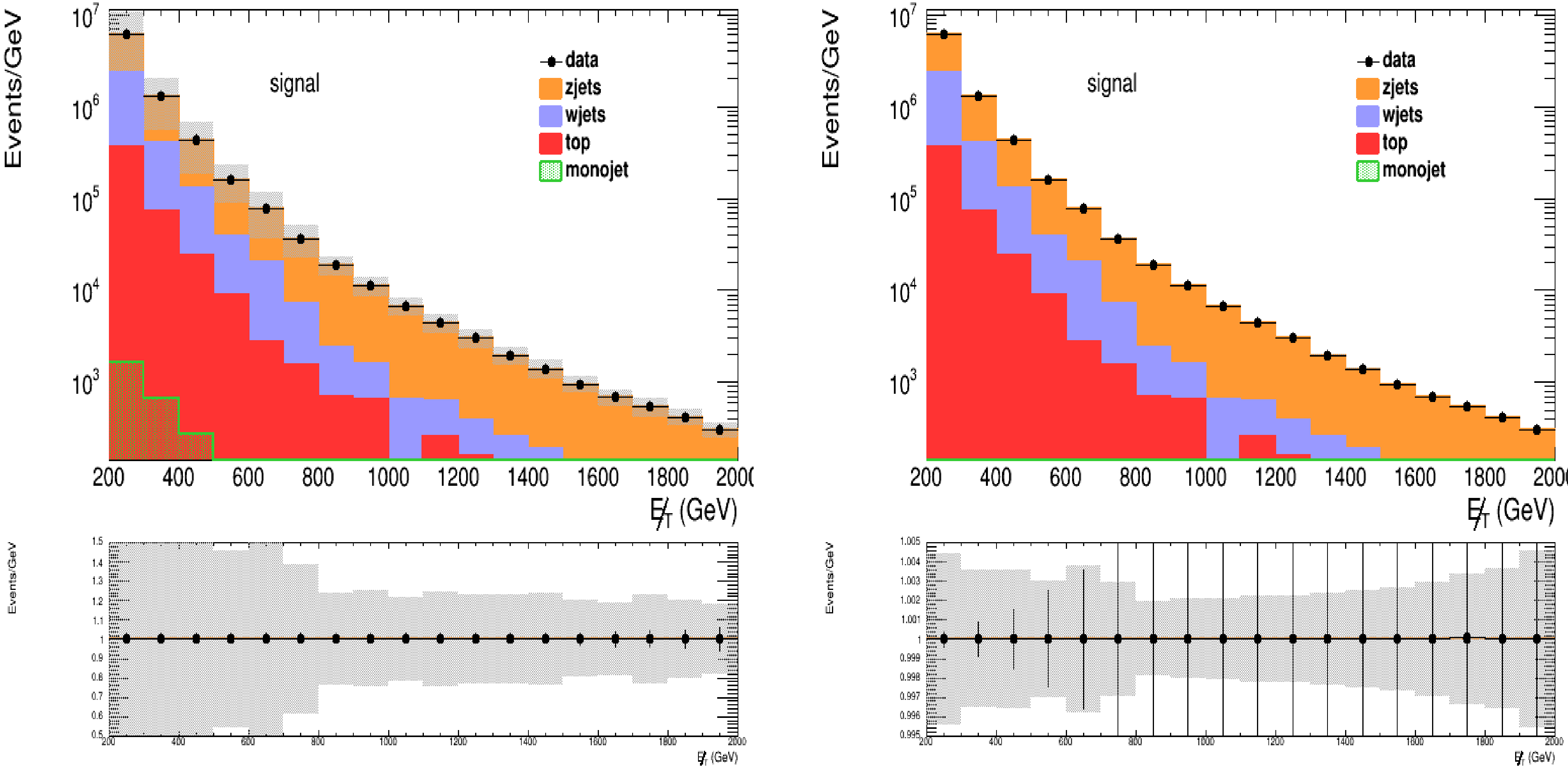
- What are reasonable uncertainty choices



- Consider two options :
  - A Loose uncertainty →Comparable to NLO
  - A Tight uncertainty →Comparable to NLO
- Using : 0.5%/0.25%/5% e/μ/τ efficiency & 1% lumi

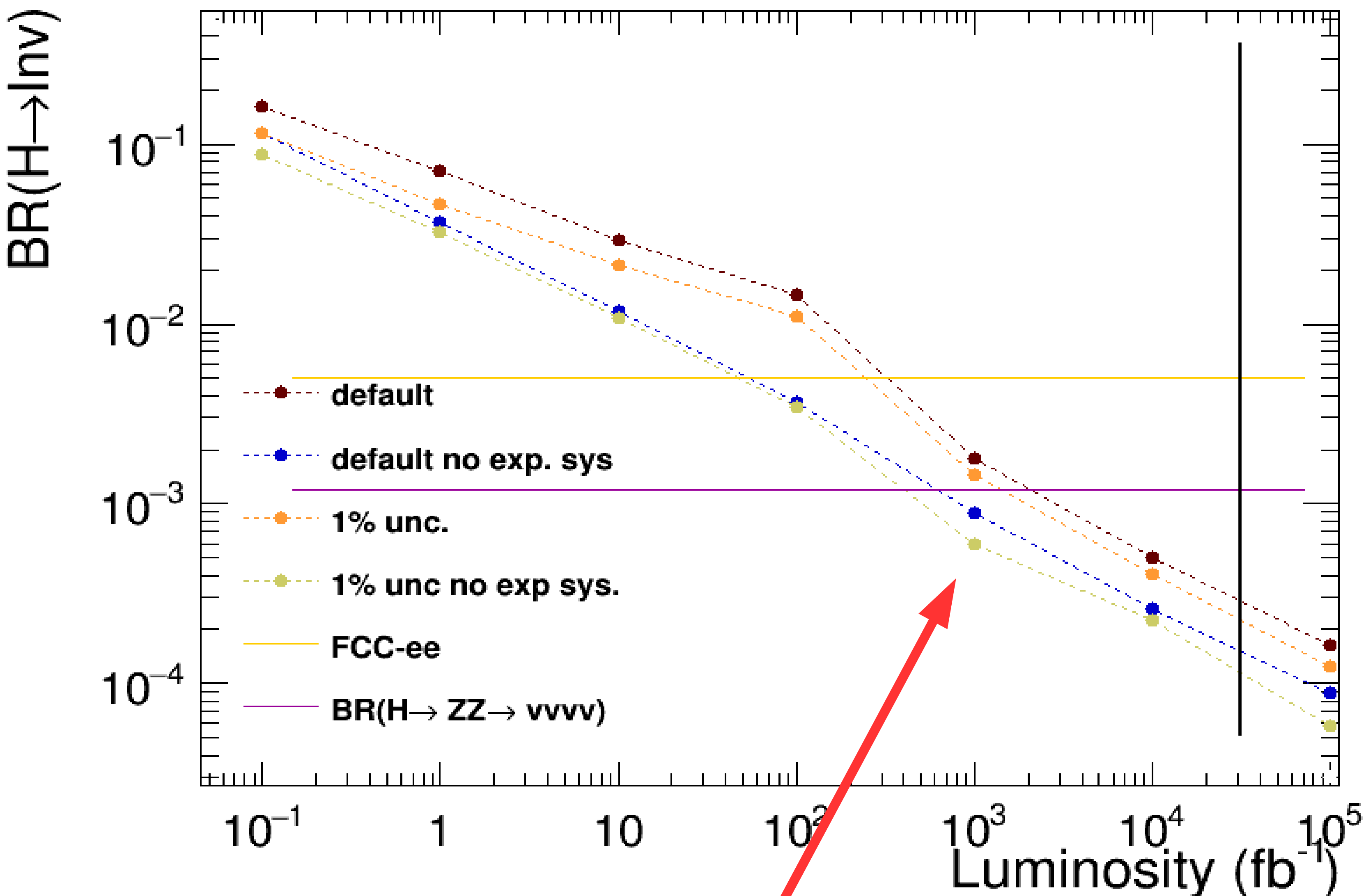
What is the precision?

- Can probe a few % effects (NNLO precision)



Through this scheme we can probe boson pT to 10^{-4} level

How do things scale?

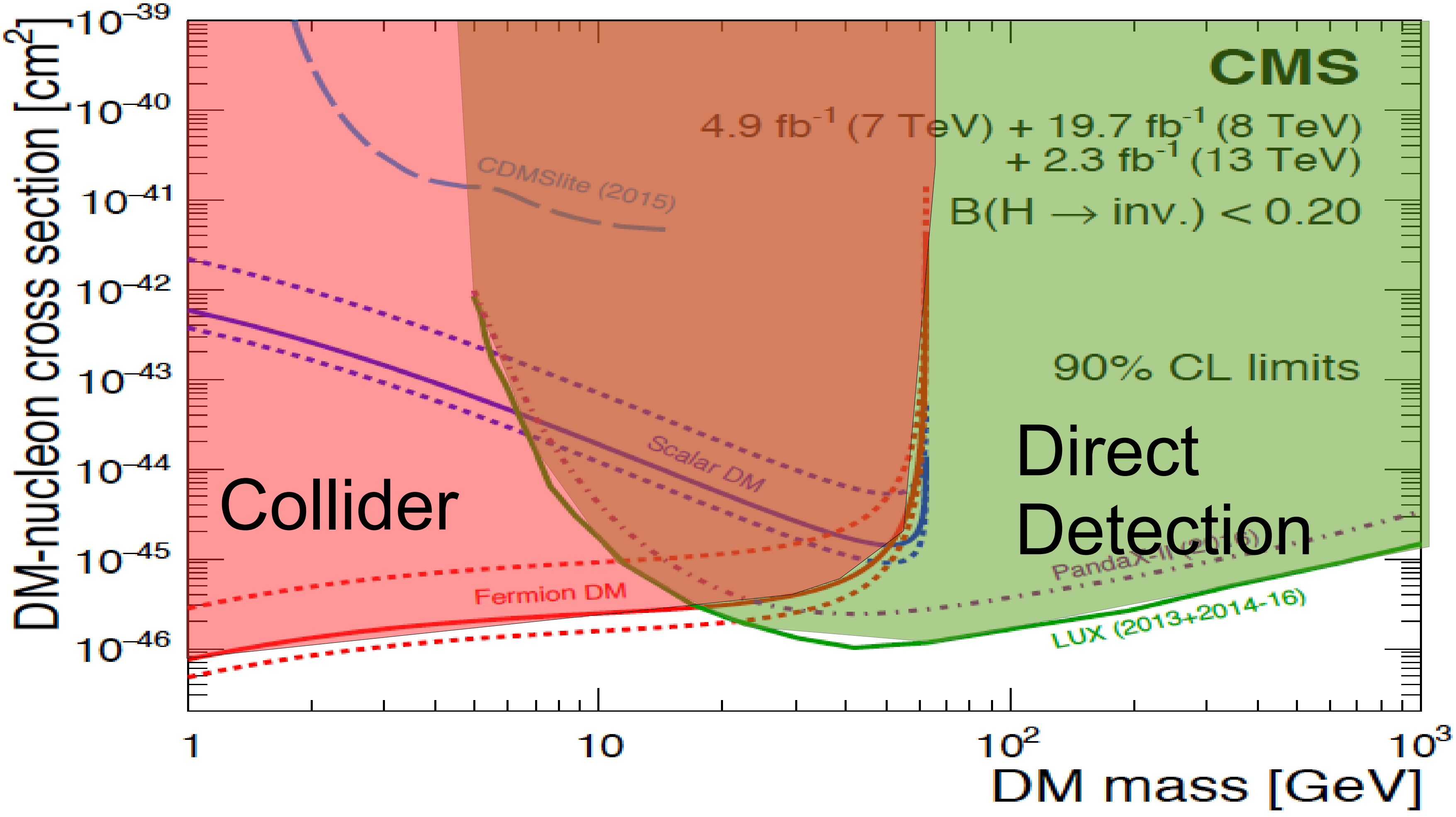


Cross the SM neutrino wall at FCC with < 1 ab^{-1}

There is no systematics wall

Current Bounds

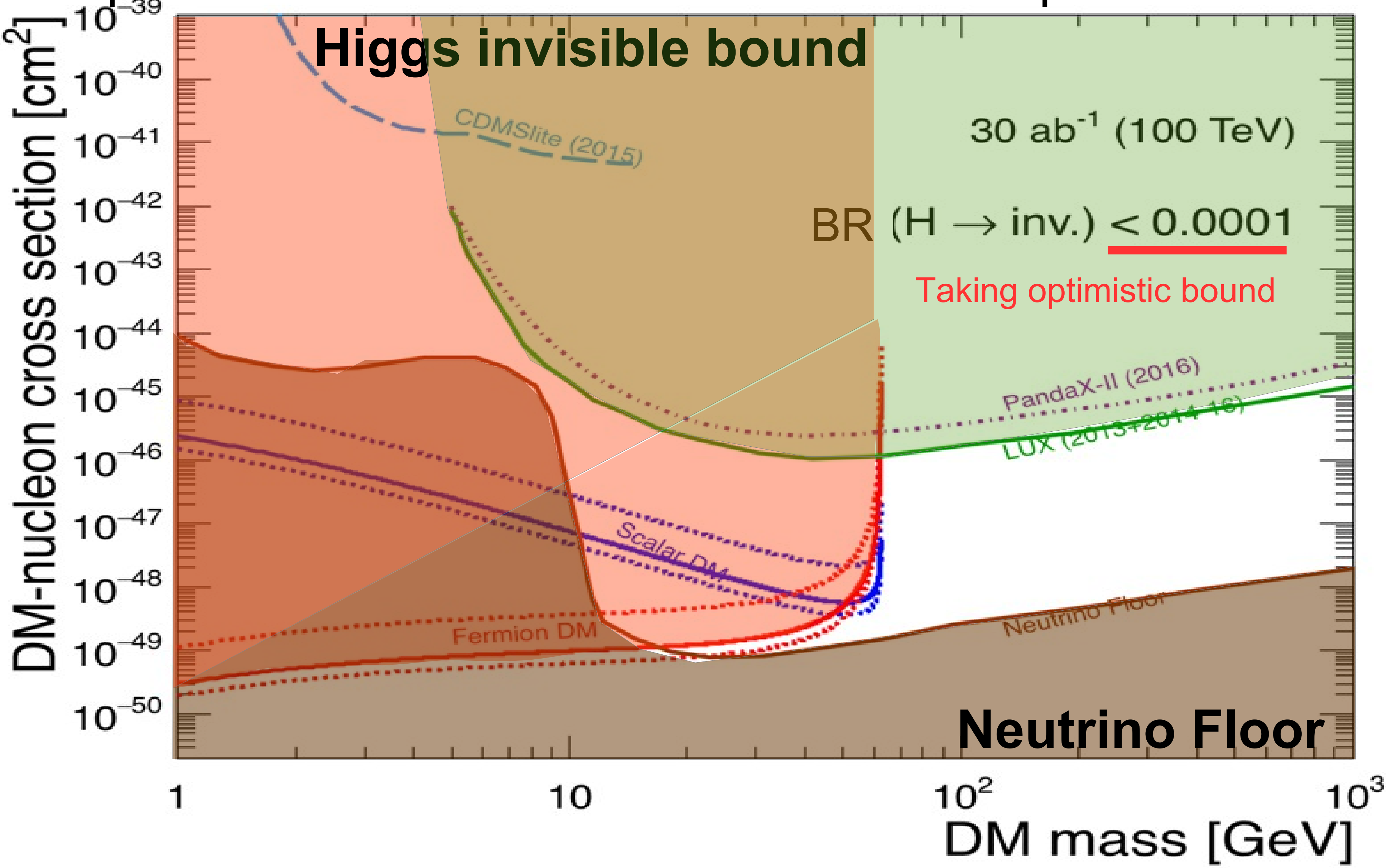
- Higgs to invisible :
  - Direct detection and collider are head to head



Competitive with the best direct detection experiments

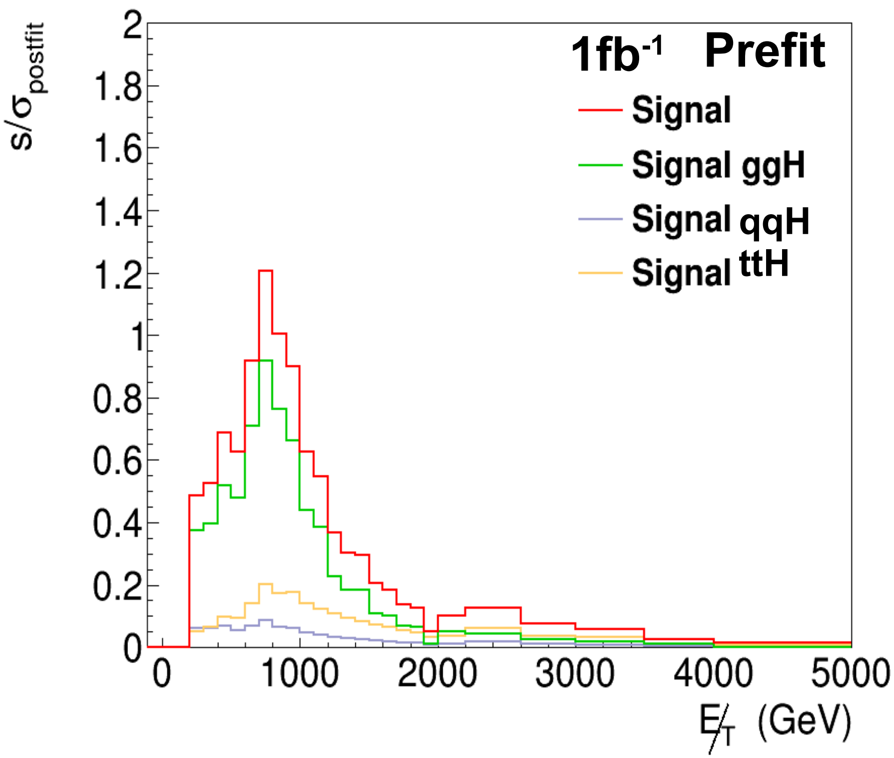
Future Bounds

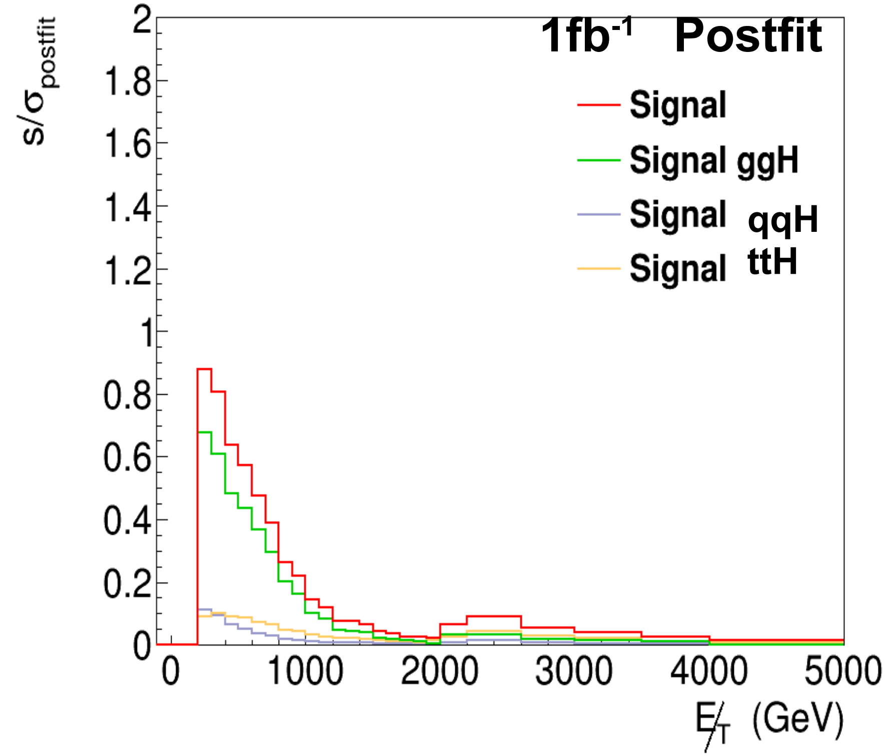
Competitive with the best direct detection experiments



Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

Understanding sensitivity





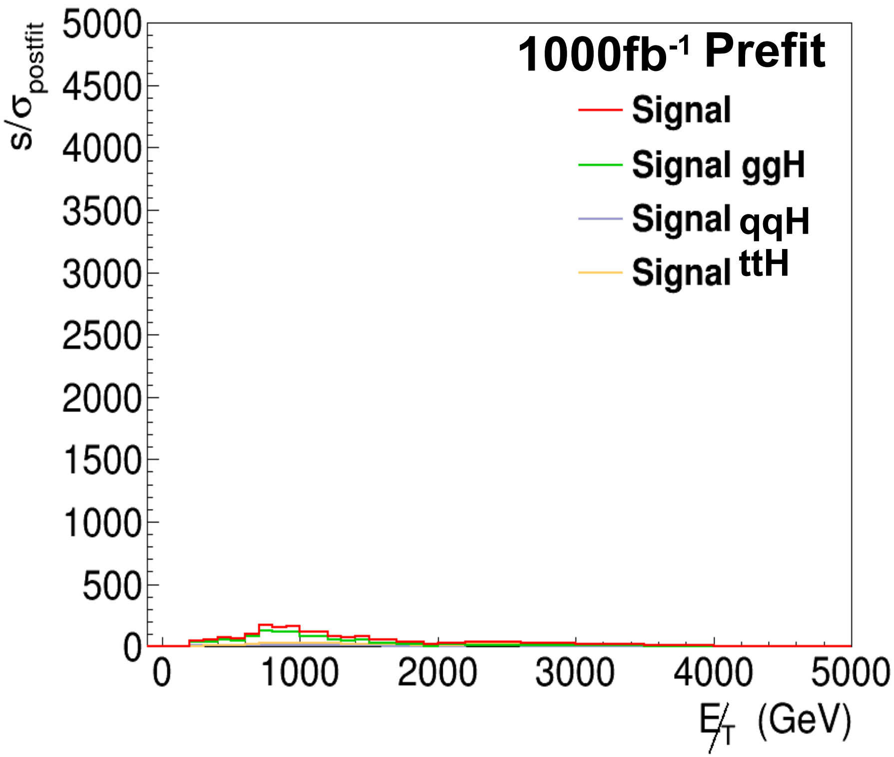
In both cases monojet dominates tt+H signal for sensitivity

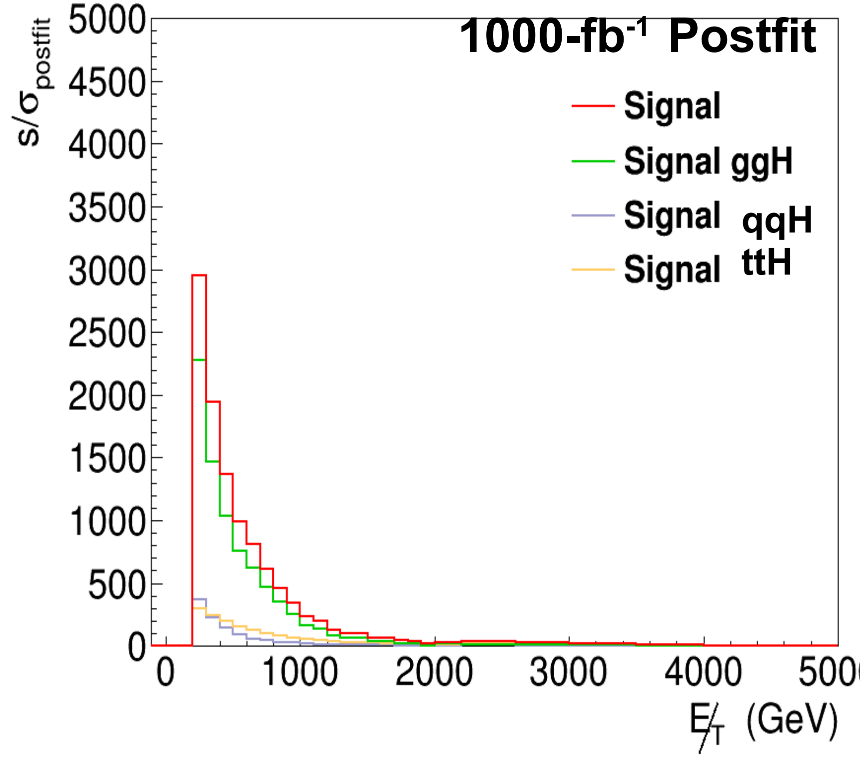
Transition to ttH happens at 1-2 TeV (note no top selection)

Postfit brings an improvement in sensitivity

Especially at low *MET*

Understanding sensitivity





In both cases monojet dominates tt+H signal for sensitivity

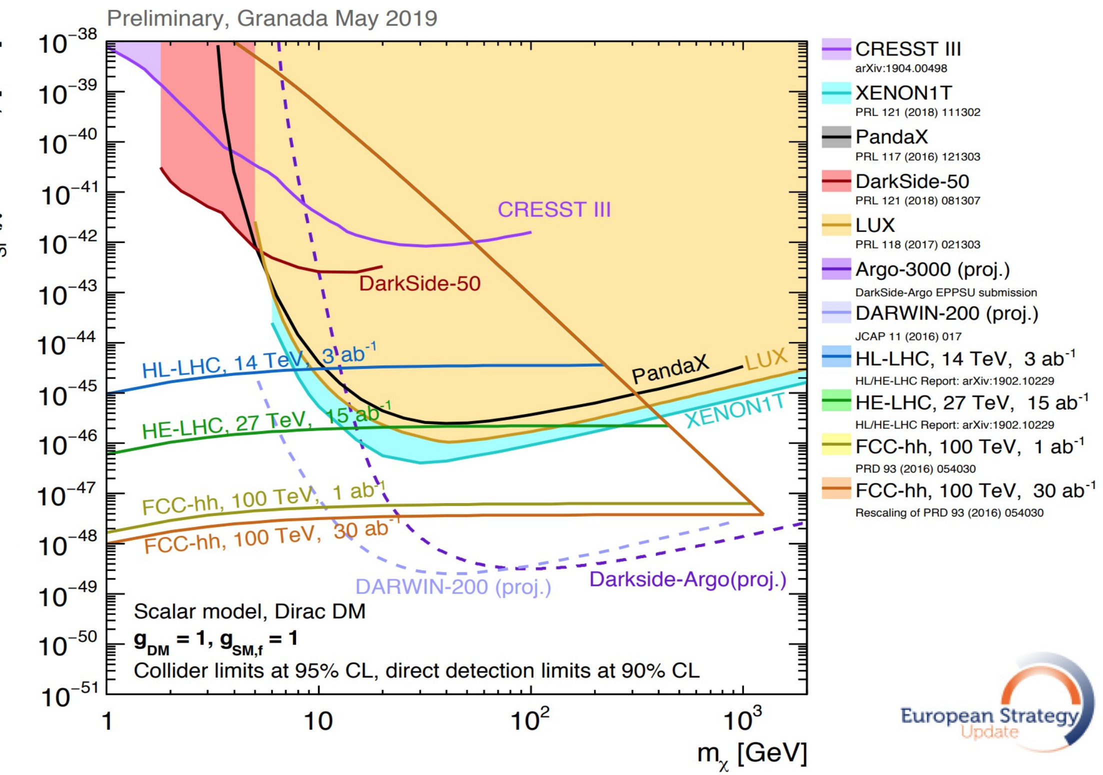
- Transition to ttH happens at 1-2 TeV (note no top selection)

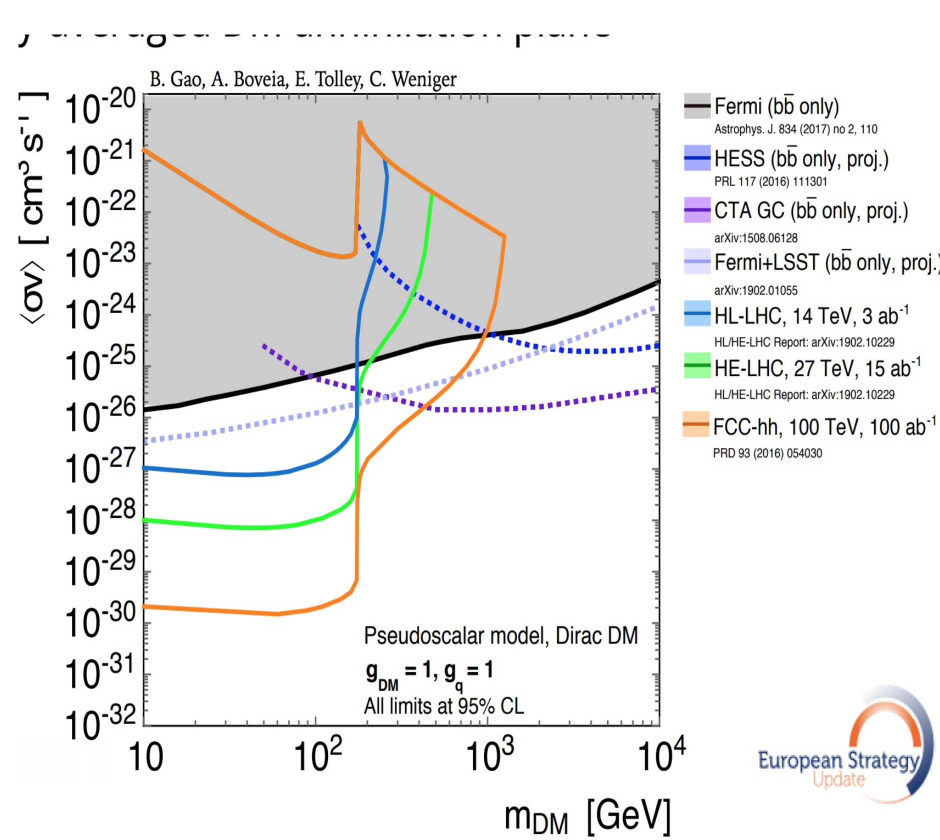
Postfit brings an improvement in sensitivity

- Especially at low *MET*

Updated Now

- Earlier versino of this analysis used in ECFA
  - Used to put
  - Thanks to Caterina Doglioni and Antonio Boveia





Conclusion

- Currently investigating H→Invisible
  - Monojet and tt+H are the dominant productions
  - Modern approach allows for scaling of limits
    - Result scales with luminosity
    - Systematic choice is critical for search
- Improving the search:
  - Better understanding of the Higgs p_T needed
  - Good theory understanding → now there!
- For Higgs Invisible we find that :
  - We can reach the neutrino wall SM H→Invisible
    - Best BR(H→Invisible) < 1-2x10^{-4}

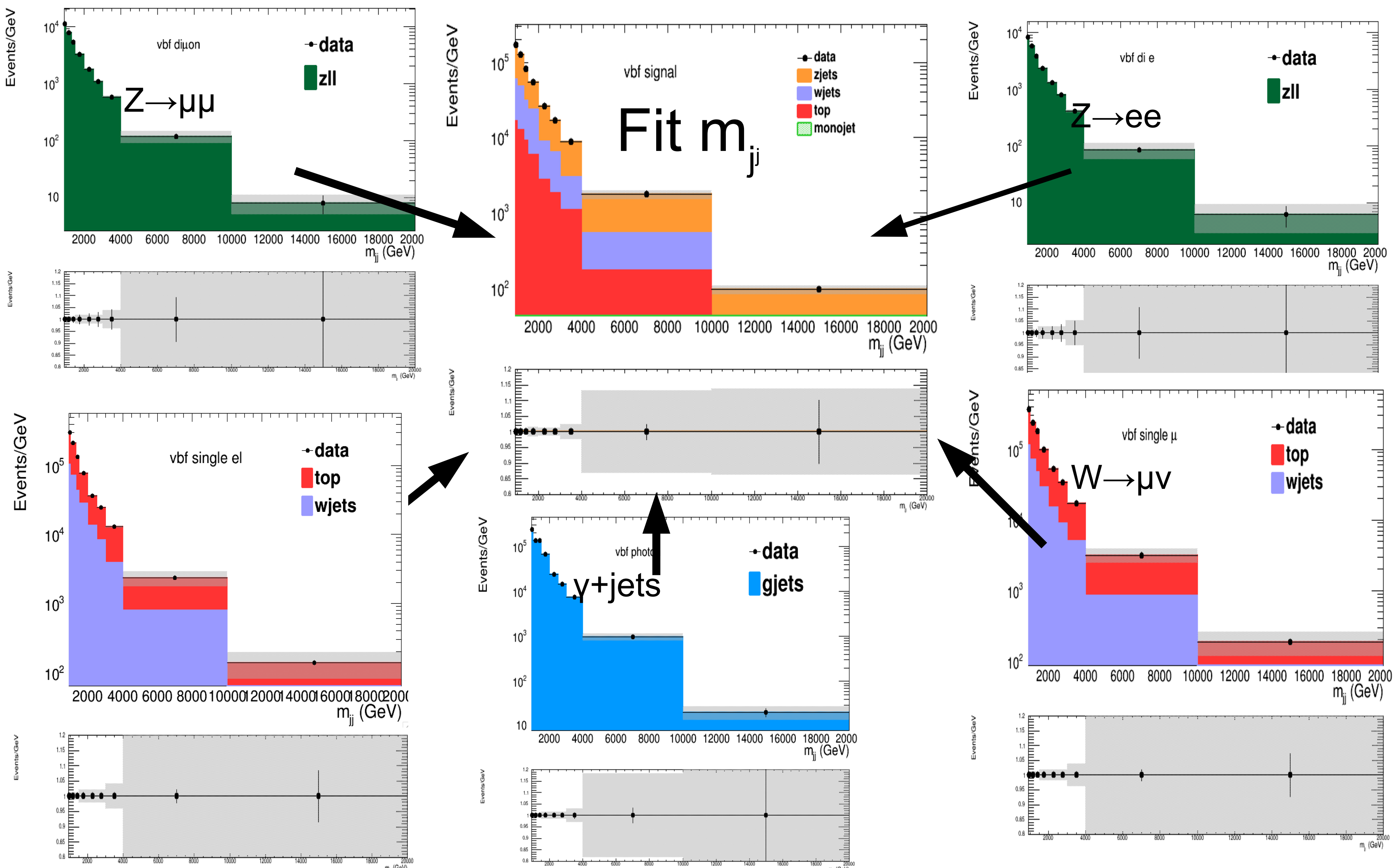
Thanks!

Generation Details

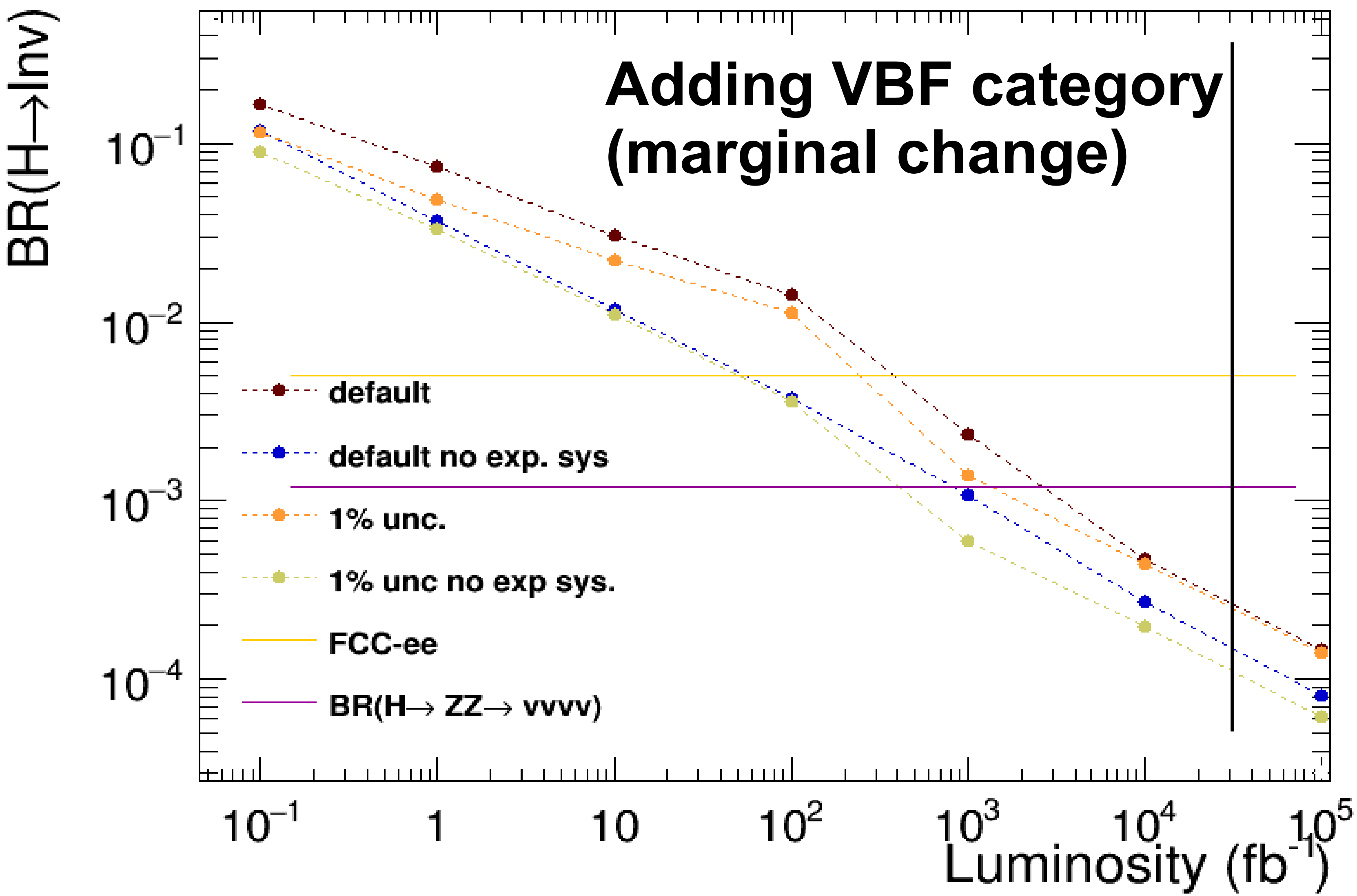
- ggH:
  - Generation now following finite top mass + 1 jet
    - Using inclusive shower
  - Applying an N/NLO k-factor (x2 NLO)(x1.25 for NNLO)
- TTH:
  - LO generation 0/1 jet + tt + h merged with MLM
  - Applying an NLO k-factor (x1.3-yellow report)
- qqH:
  - LO generation 2/3 jet for VBF and VH combined
  - No k-factor (known to be small)
- Backgrounds : Now using MG weighted generation
  - Weighting by roughly $w \sim HT^3$

VBF analysis @ CMS

VBF analysis is a 2 category version (*MET* for m_{jj} < 900)

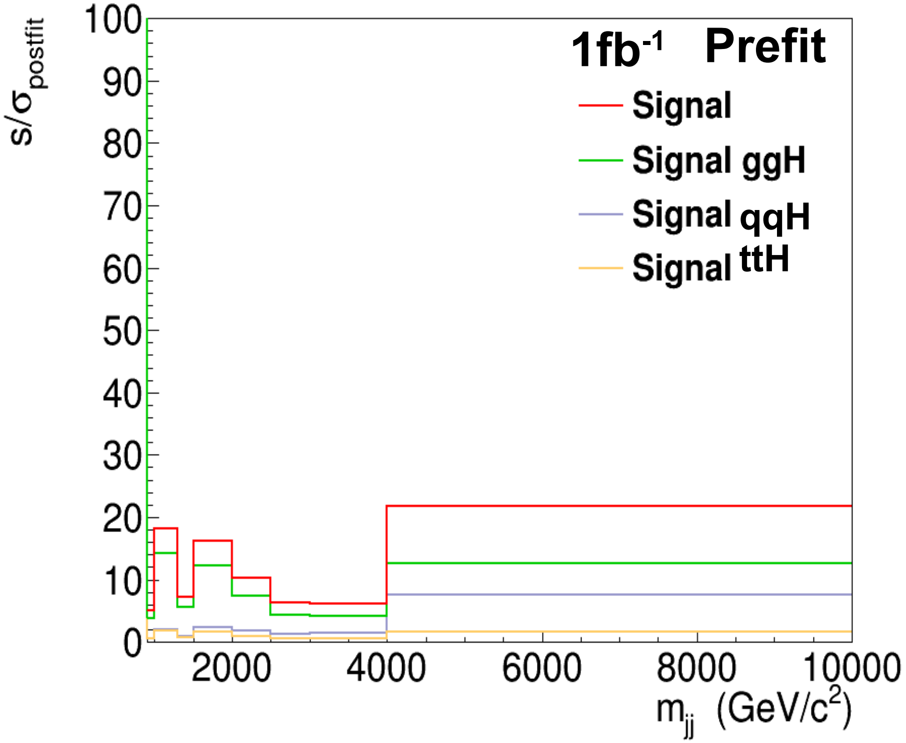


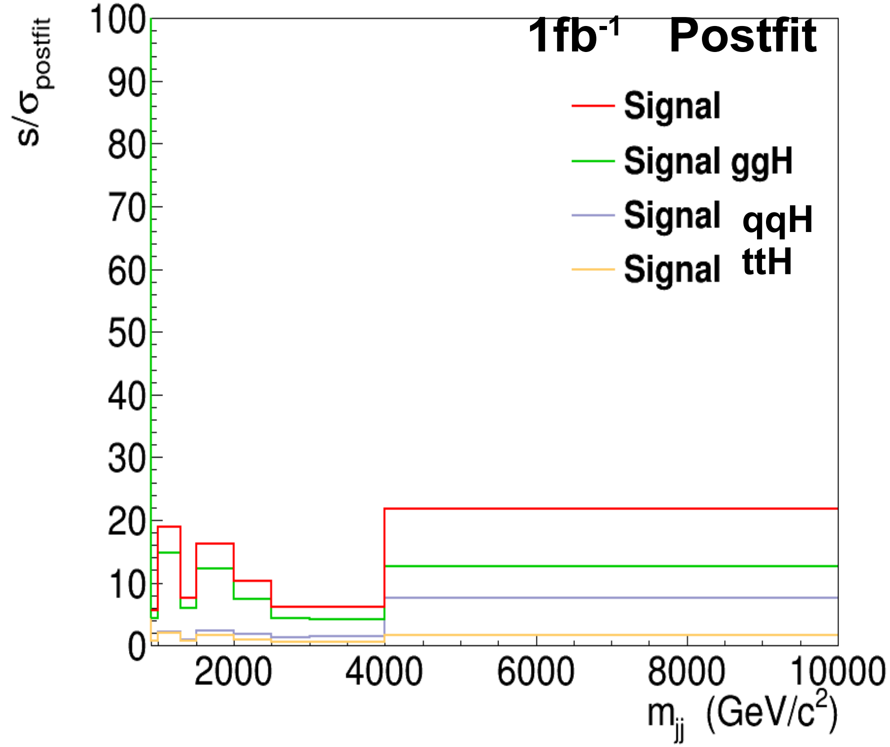
How do things scale?



Cross the SM neutrino wall at FCC with < 1 ab^{-1}

Understanding sensitivity





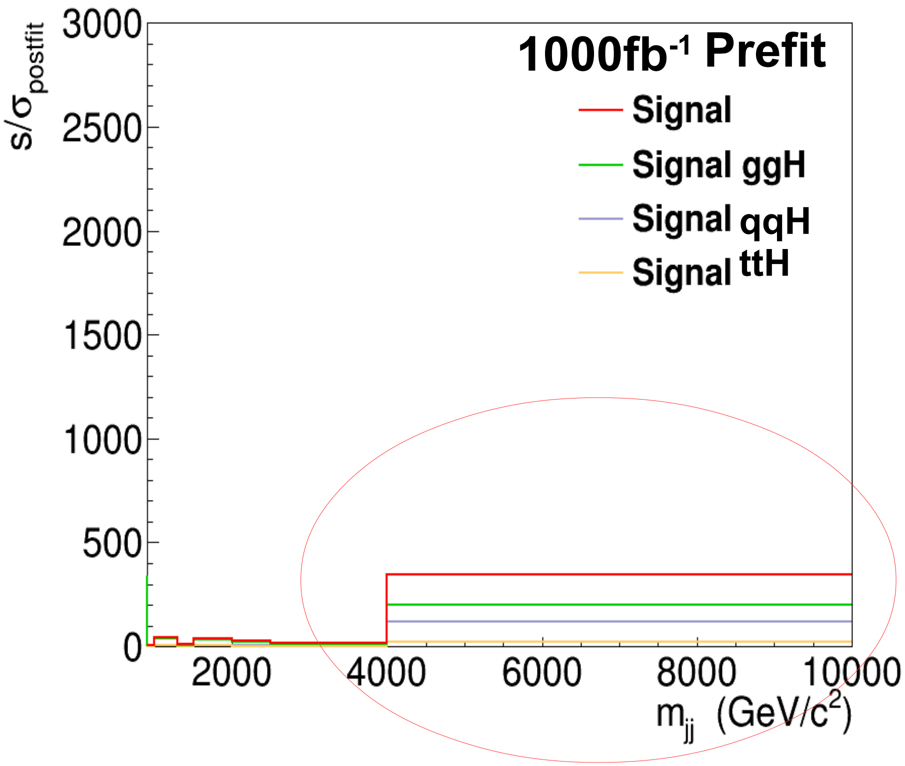
Prefit and postfit show limited gains in sensitivity

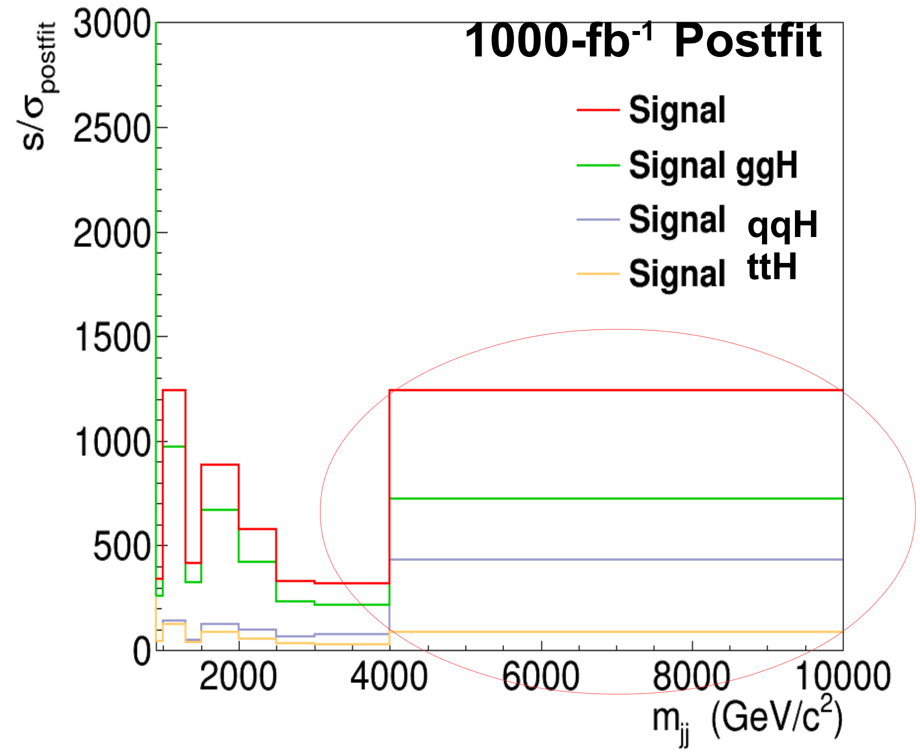
Not enough events to do real constraints

The VBF channel starts to dominate in the last bins

It doesn't drivet the sensitivity

Understanding sensitivity



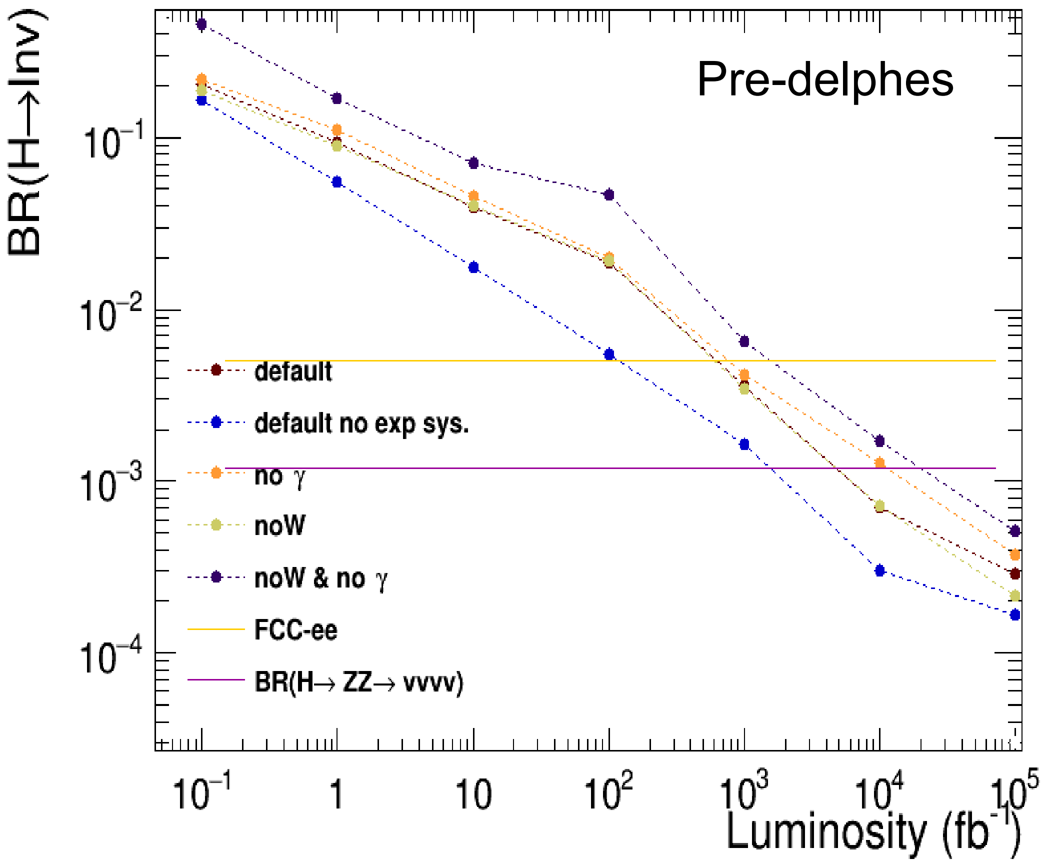


Constraints bring significant gains from low m_{jj} region

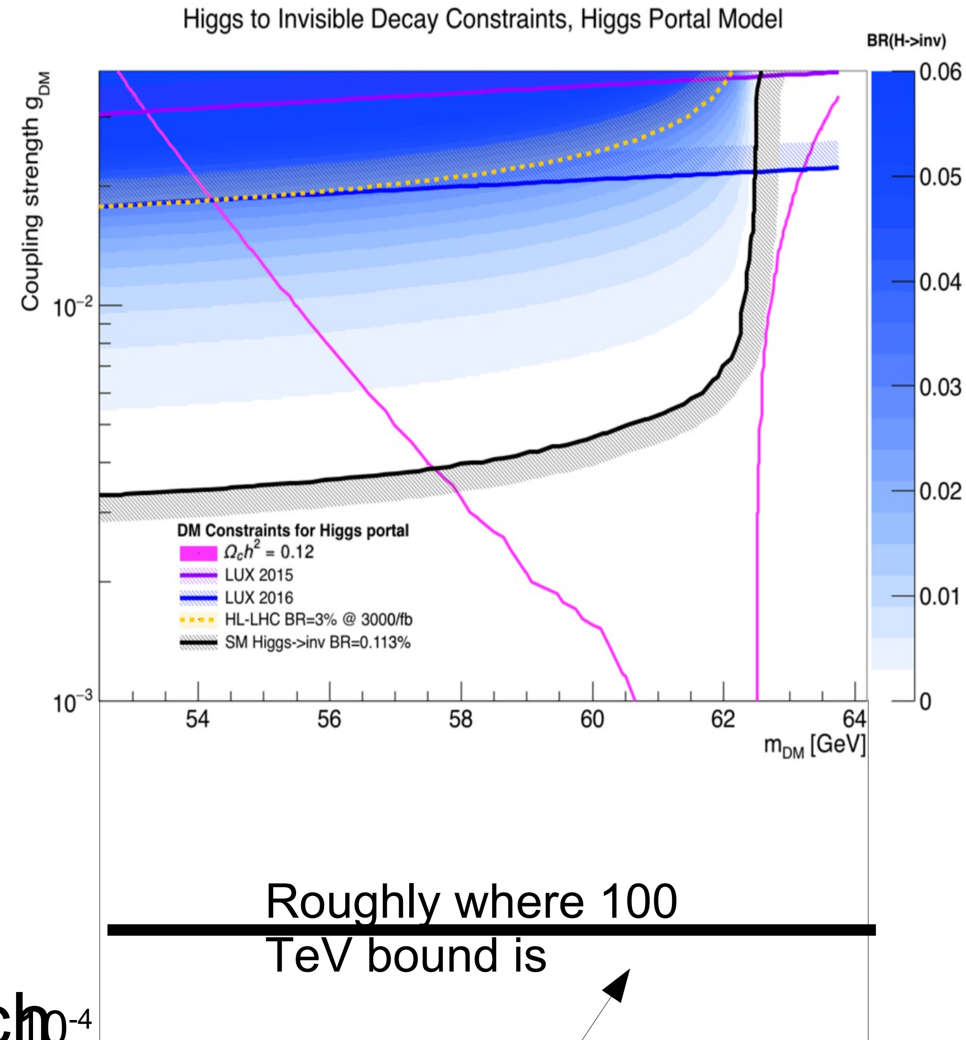
Constraints from control regions re substantial in fit

The intuition of signal importance changes completely

What is the impact?

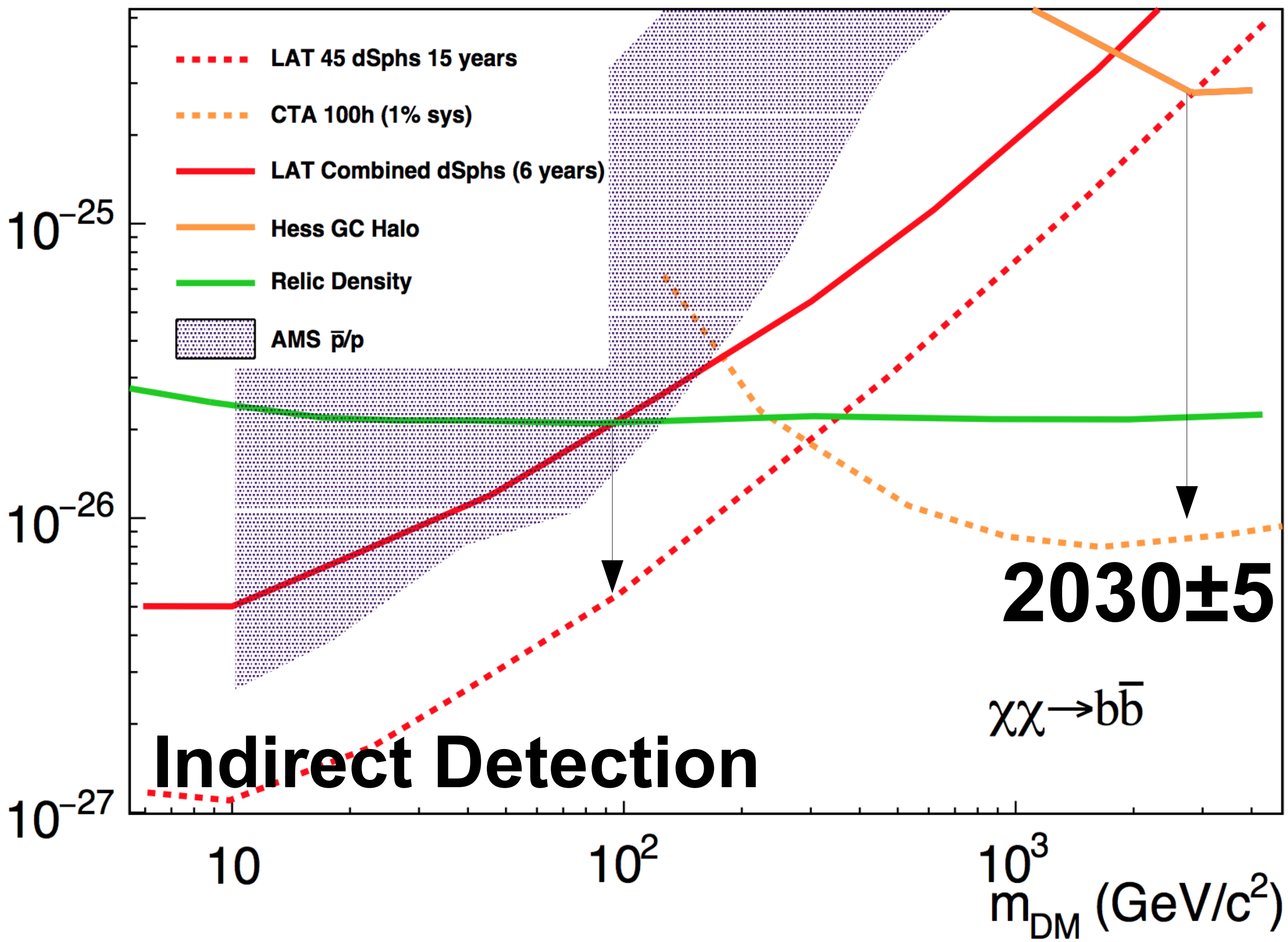


Relying on the Z boson gives a substantial reduction in the search



Equivalent mass splitting to be < 1 GeV (given relic)

Dark Matter searches not @ collider



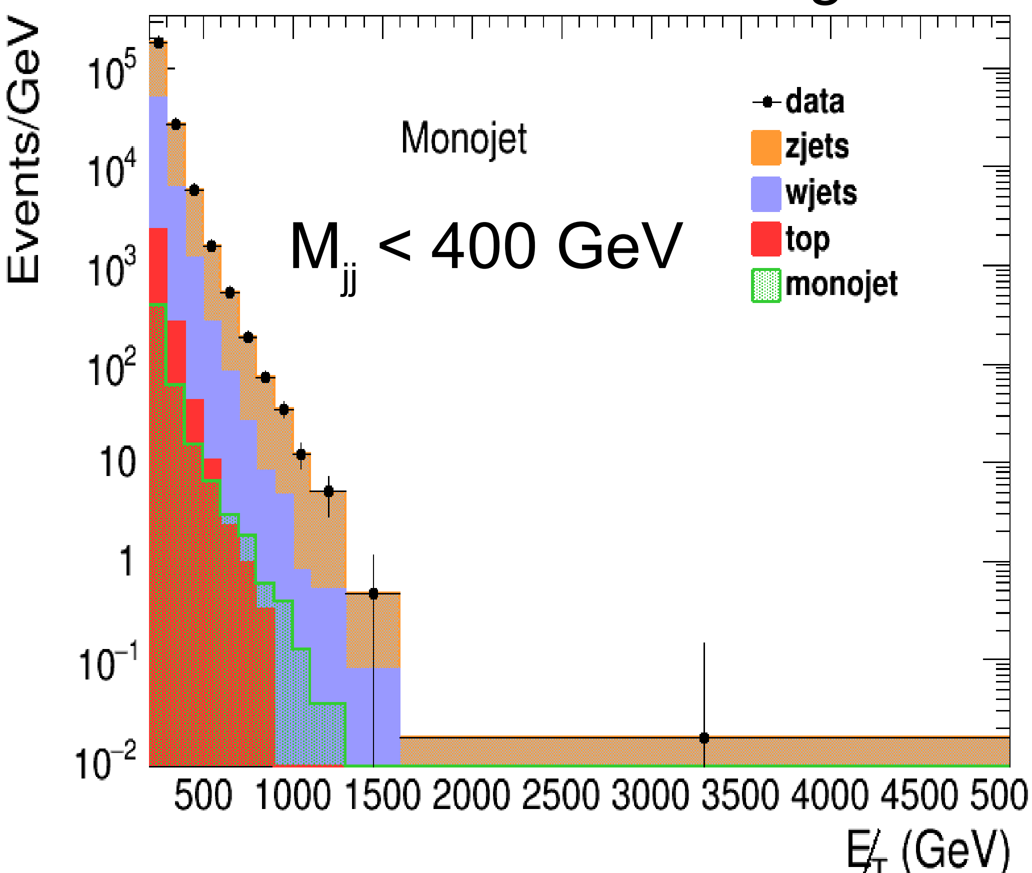
Goal: get to the Relic density

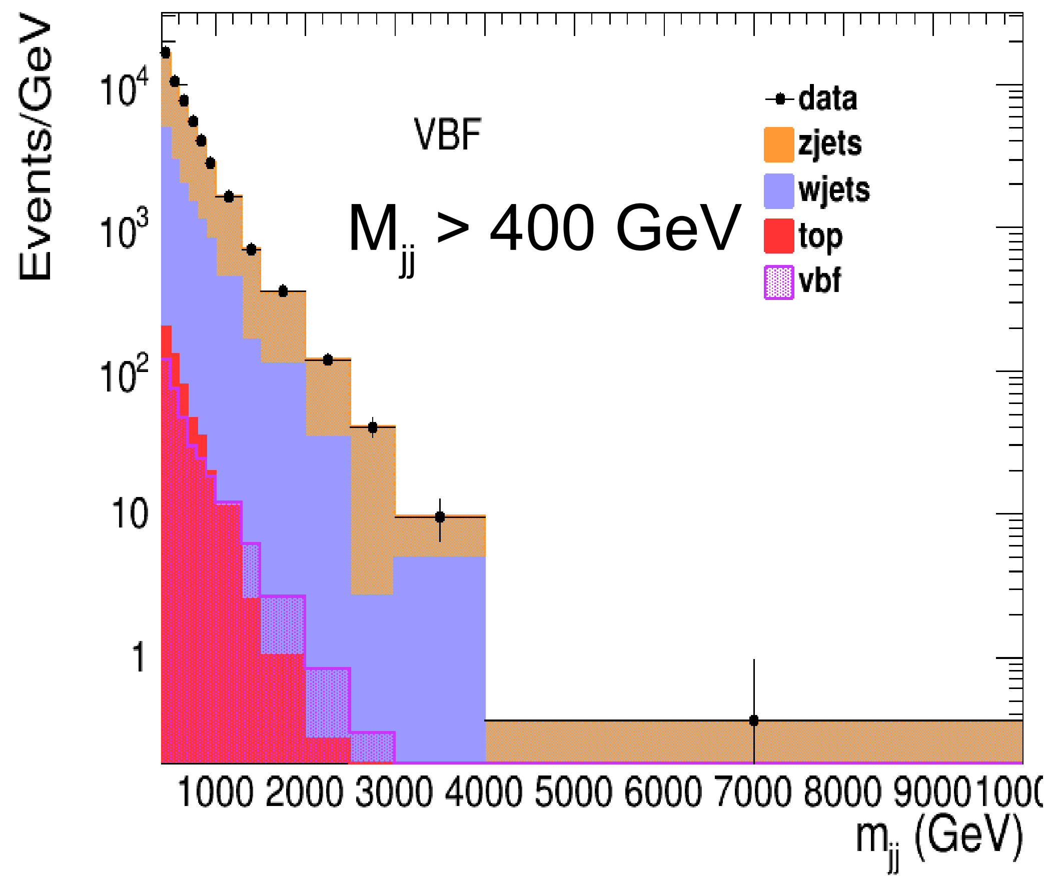
The 100 TeV DM Benchamark*

*Same ring is being considered for e^+e^- collider (its not relevant for DM)

Improving the Projections

- Following recent studies :
  - Perform an updated version of the Higgs to invisible
  - Do a simultaneous fit of *MET* and M_{jj} distribution
    - Use full control region framework that will be discussed later





A common theme of DM talks

- Relic density is solved for a constant value of:

$$(g_q g_{DM})^2 = C$$

Hardest challenge

Set this to be large
still get right relic

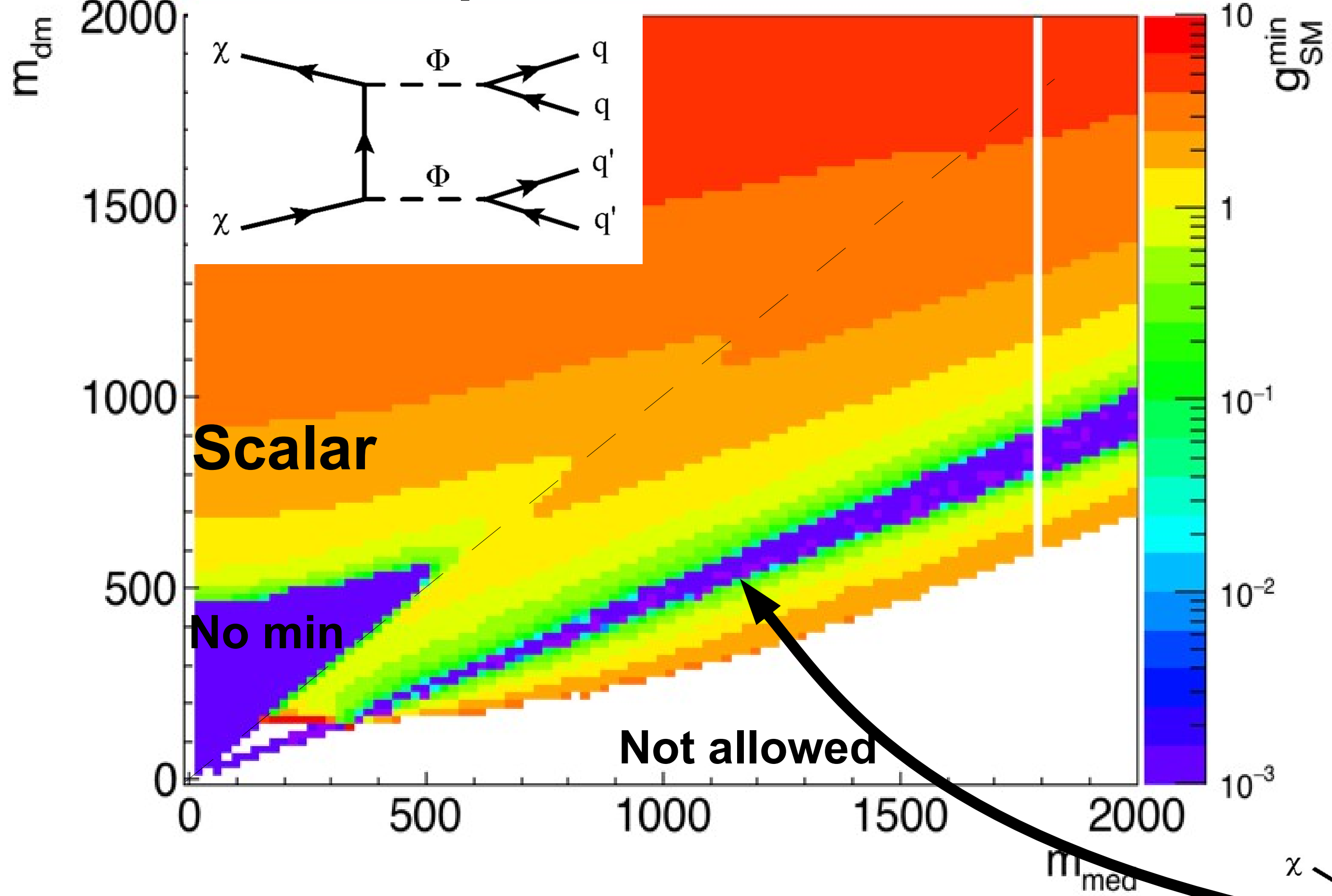
Set this to be small
Weak coupling with the SM

Most challenging dark matter searches consist of :
strong dark sector coupled weakly to the visible sector

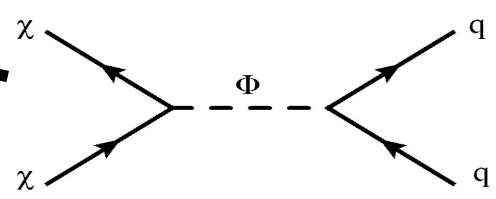
What is the smallest coupling?

- For a dark sector coupling $g_{DM}=1$

t-channel production

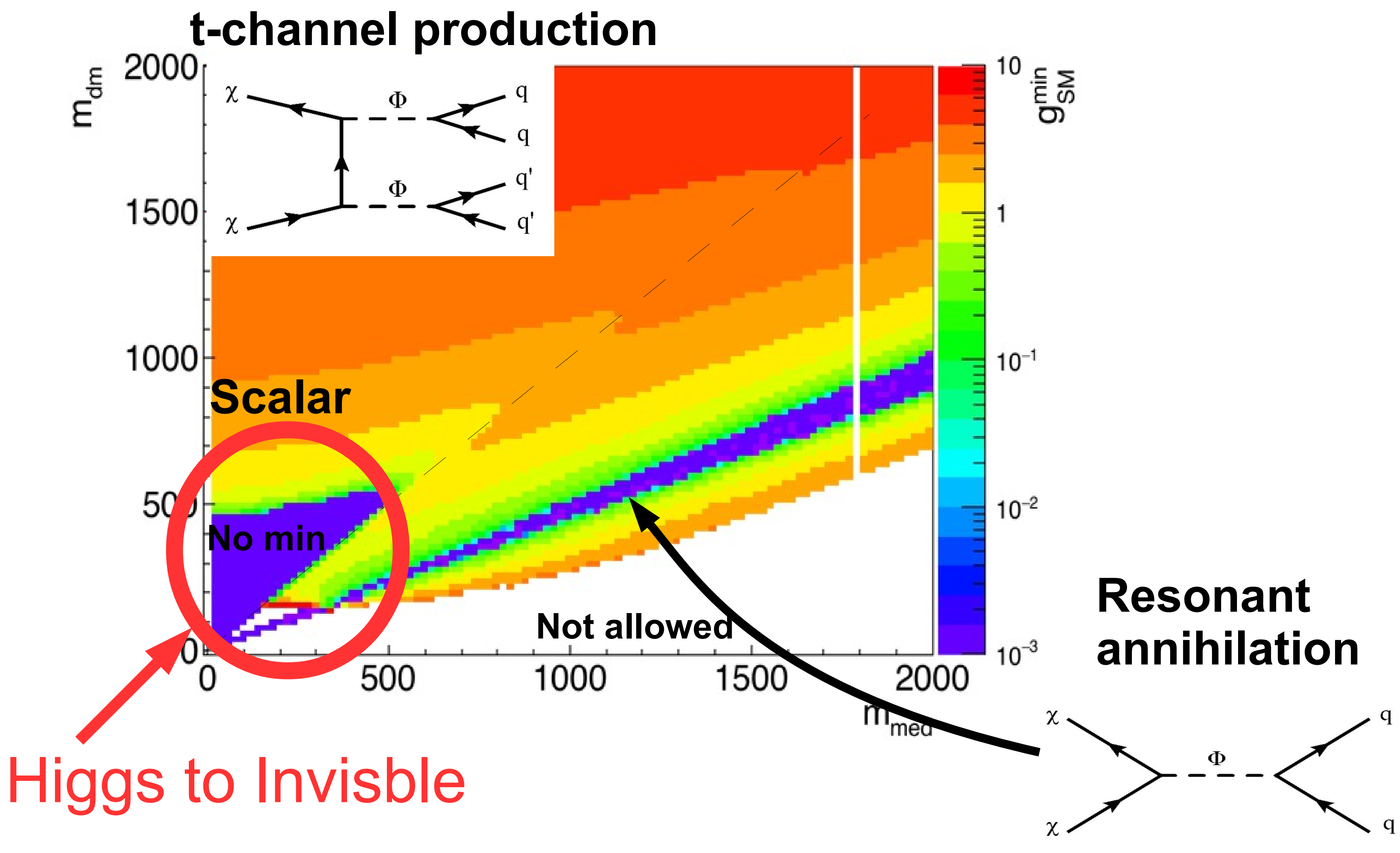


Resonant annihilation



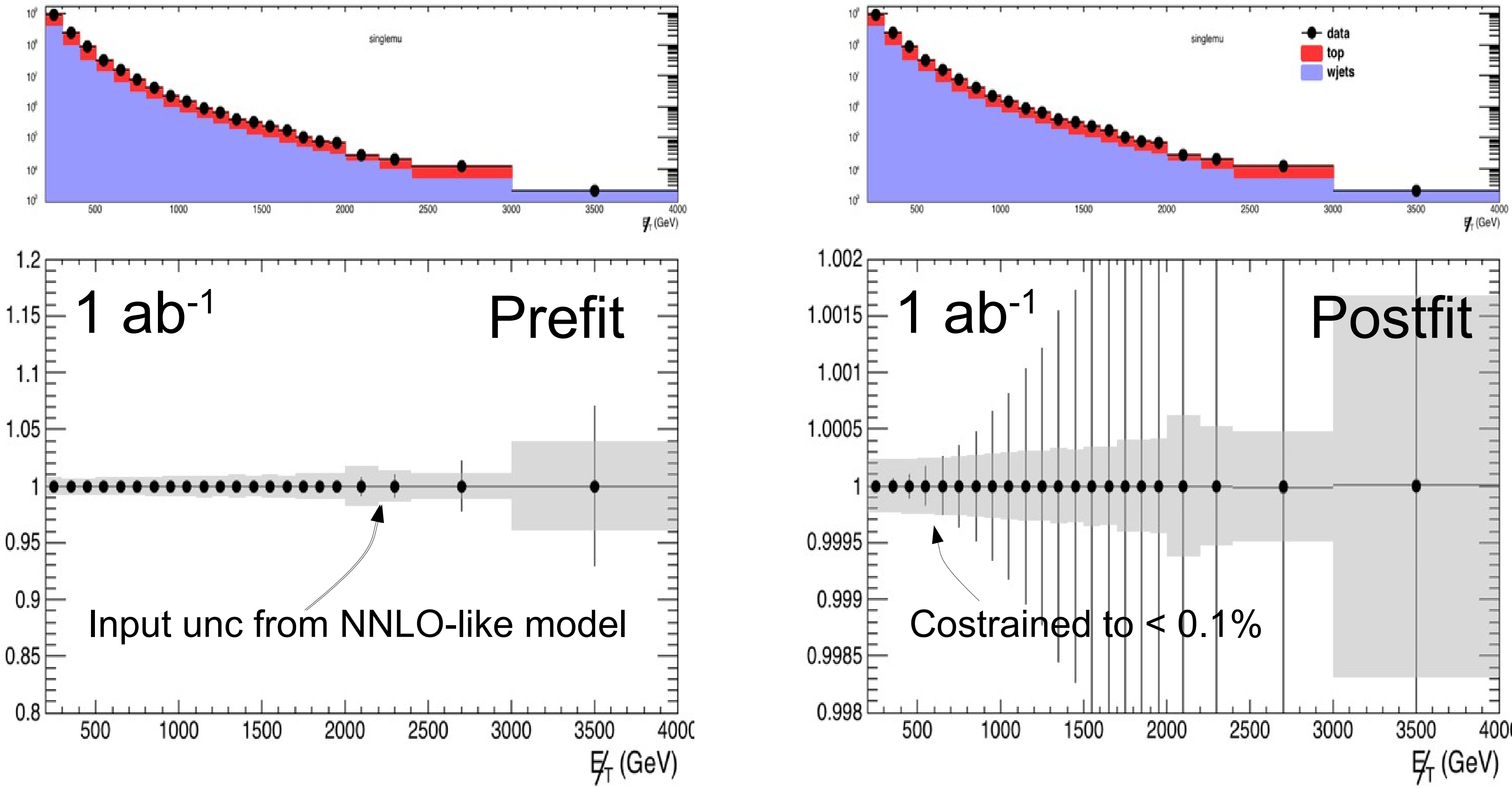
What is the smallest coupling?

- For a dark sector coupling g_{DM}=1



What is the precision?

- Can probe a few % effects (NNLO precision)



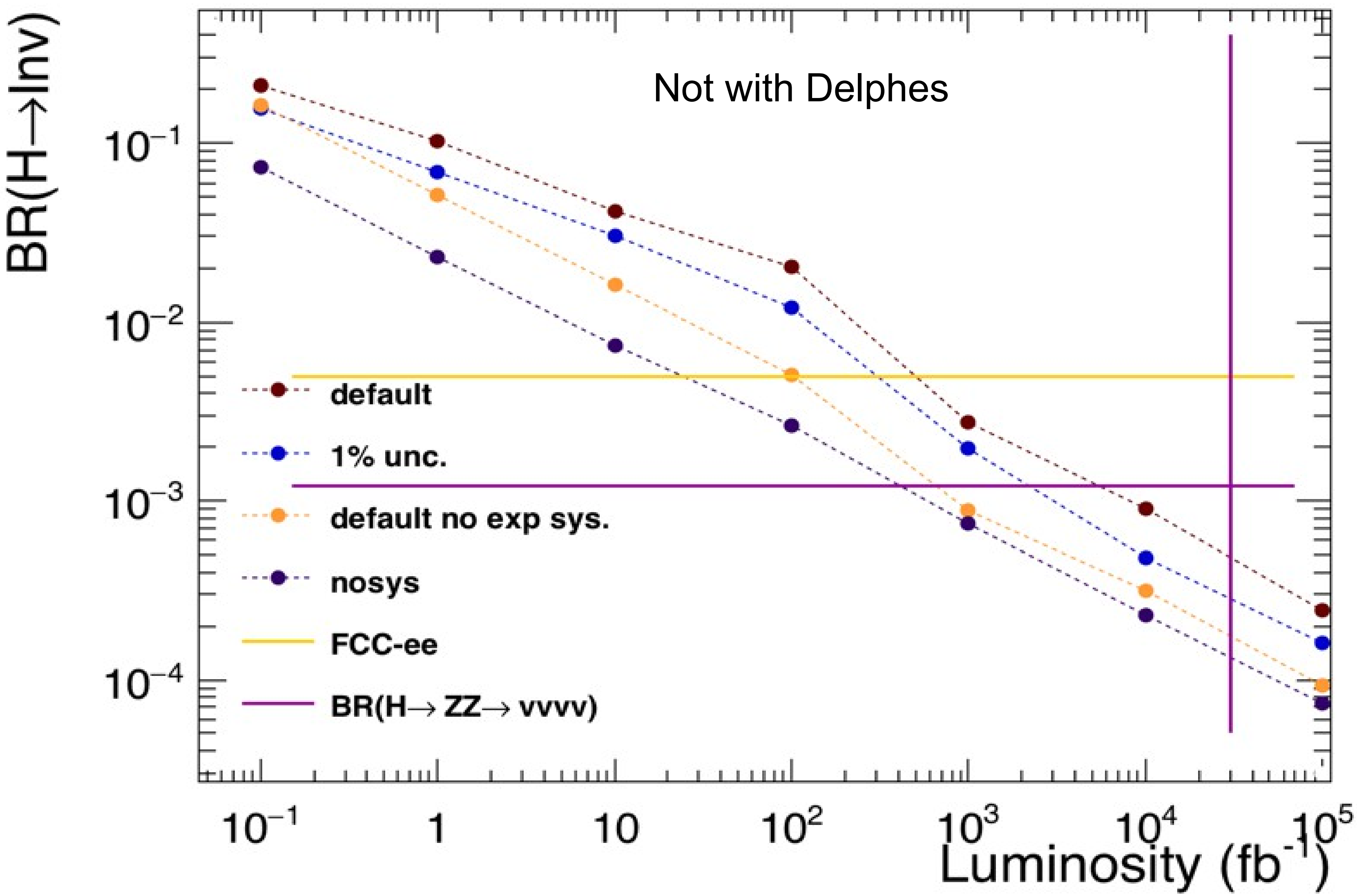
Through this scheme we can probe boson pT to 10^{-4} level

Conclusions

- A key aspect to FCC-hh is incredible rate
  - Allows us to probe Higgs invisible beyond neutrino wall
  - Extends Higgs invisible search well beyond FCC-ee
  - Extends to SM Higgs invisible
    - Gives us a signal we can calibrate
  - Higgs invisible bound translated to low mass scalar
    - Probes most of the allowed minimal coupling phase space

- Dark matter at FCC-hh
  - Four part study in High rate/High Mass/Exotics
  - In all cases: capability to exceed or match all other exp.

How do things scale?

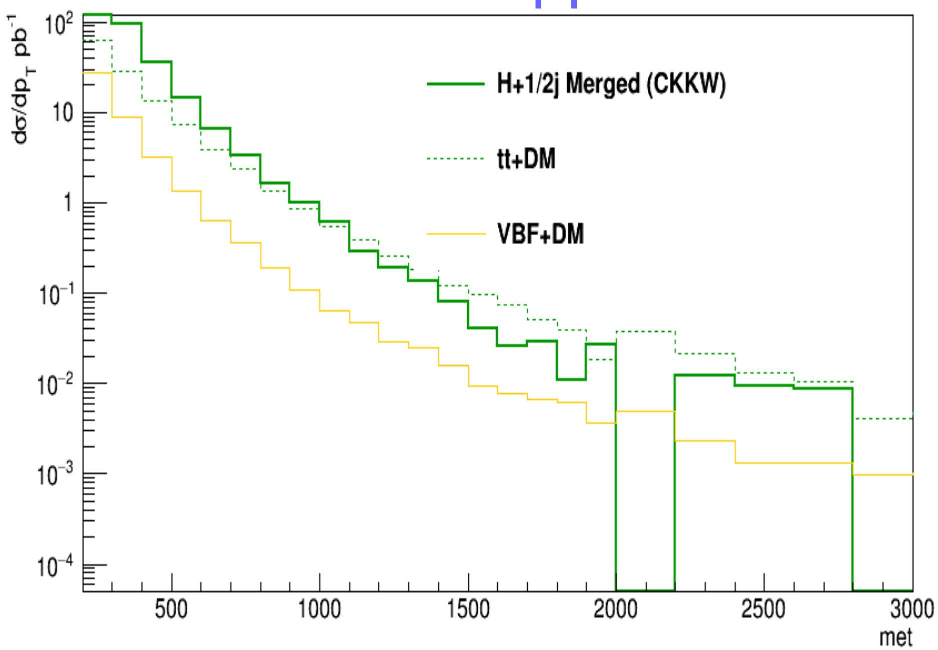


Cross the SM neutrino wall at FCC with < 1 ab^{-1}

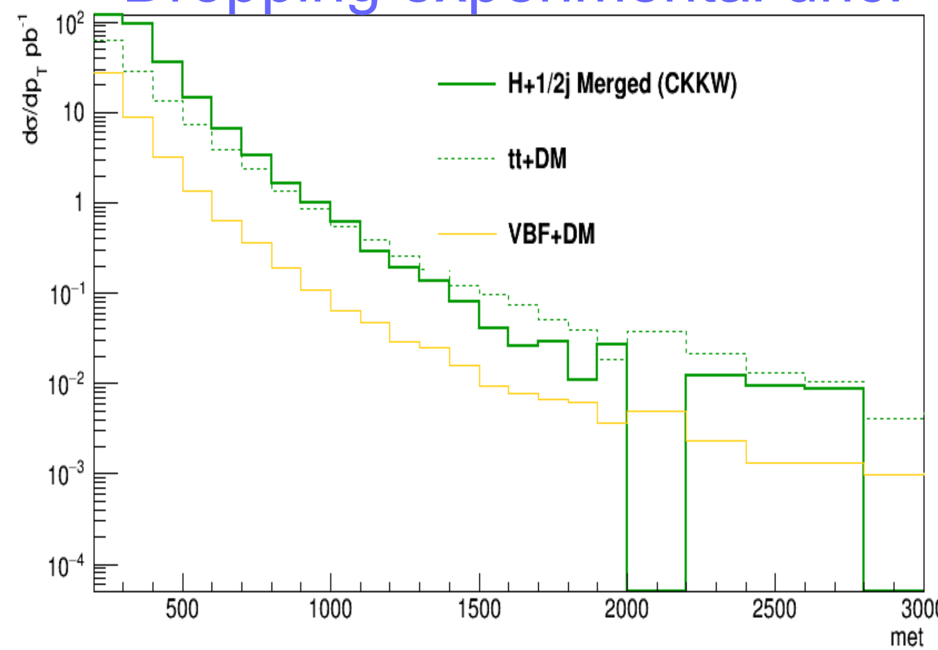
Understanding sensitivity

- 10 fb^{-1}: Changing ratio to Bin/postfit unc. σ

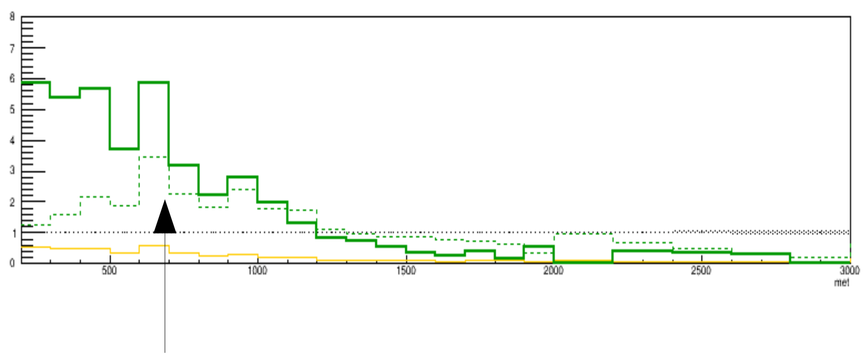
Current approach



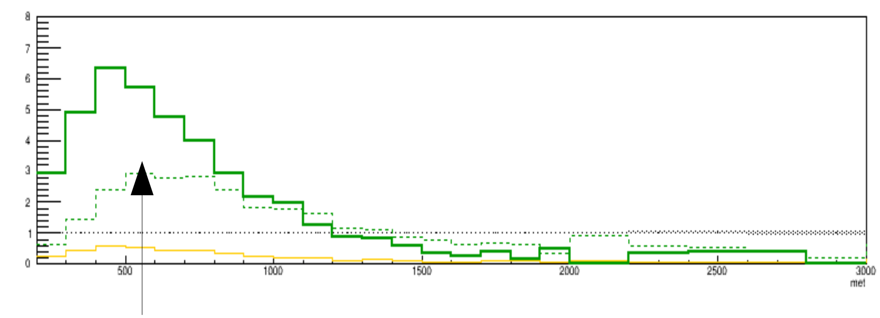
Dropping experimental unc.



In both cases monojet dominates tt+H signal for sensitivity

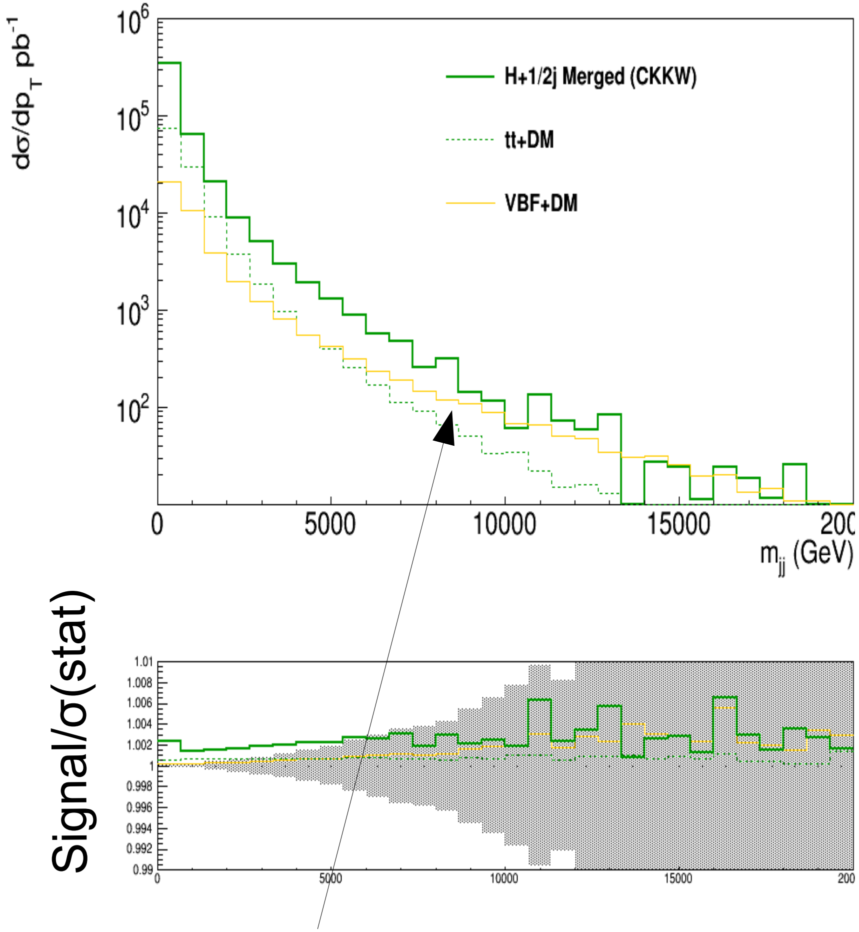


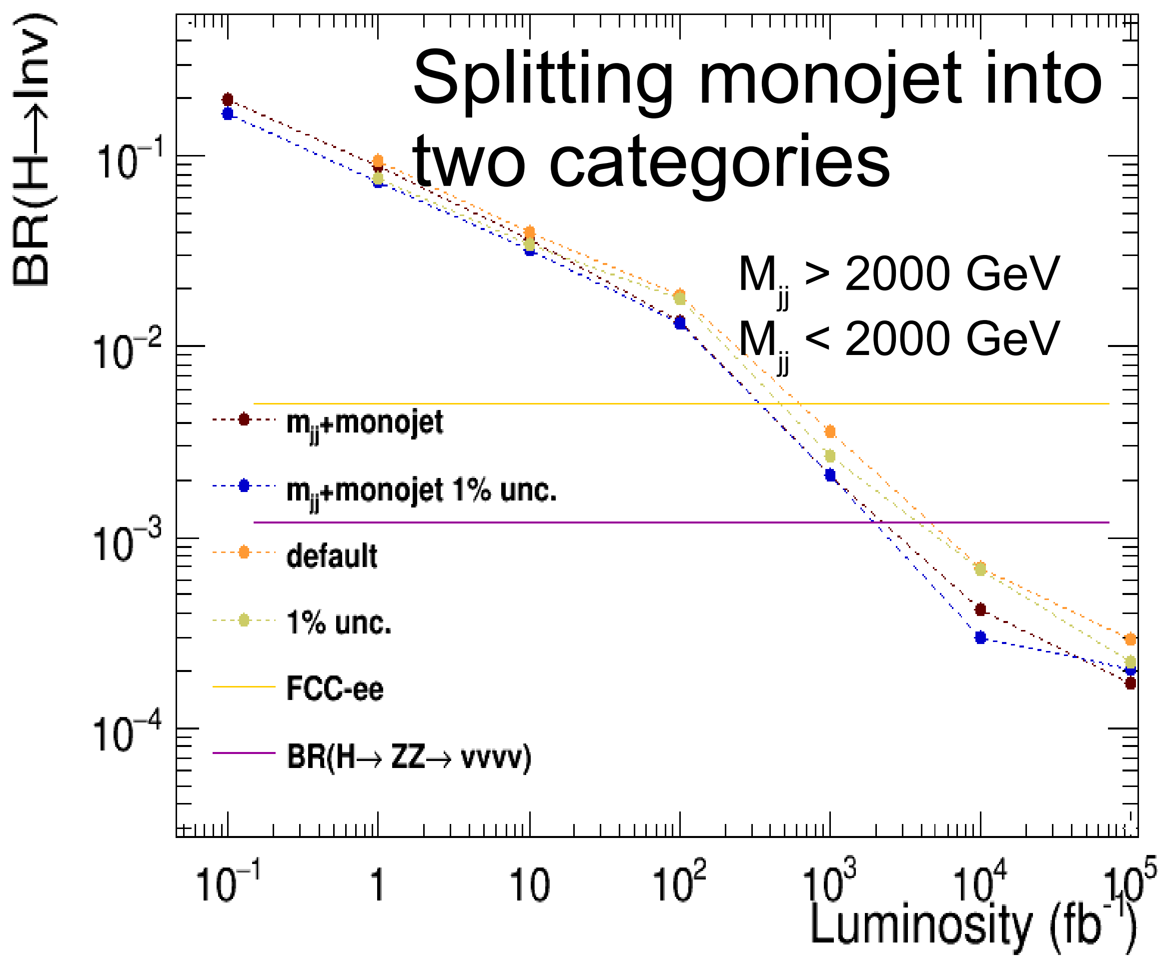
Ratio/ggH



Can we extend things?

- Can consider targetting the VBF final state?

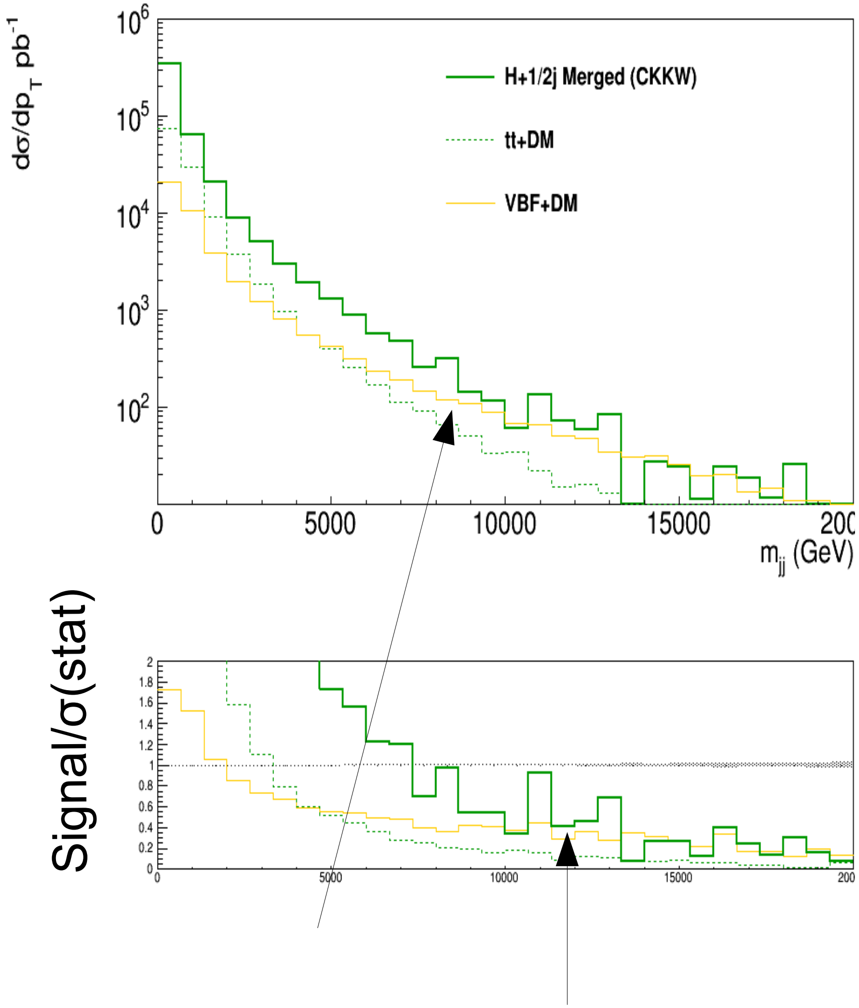


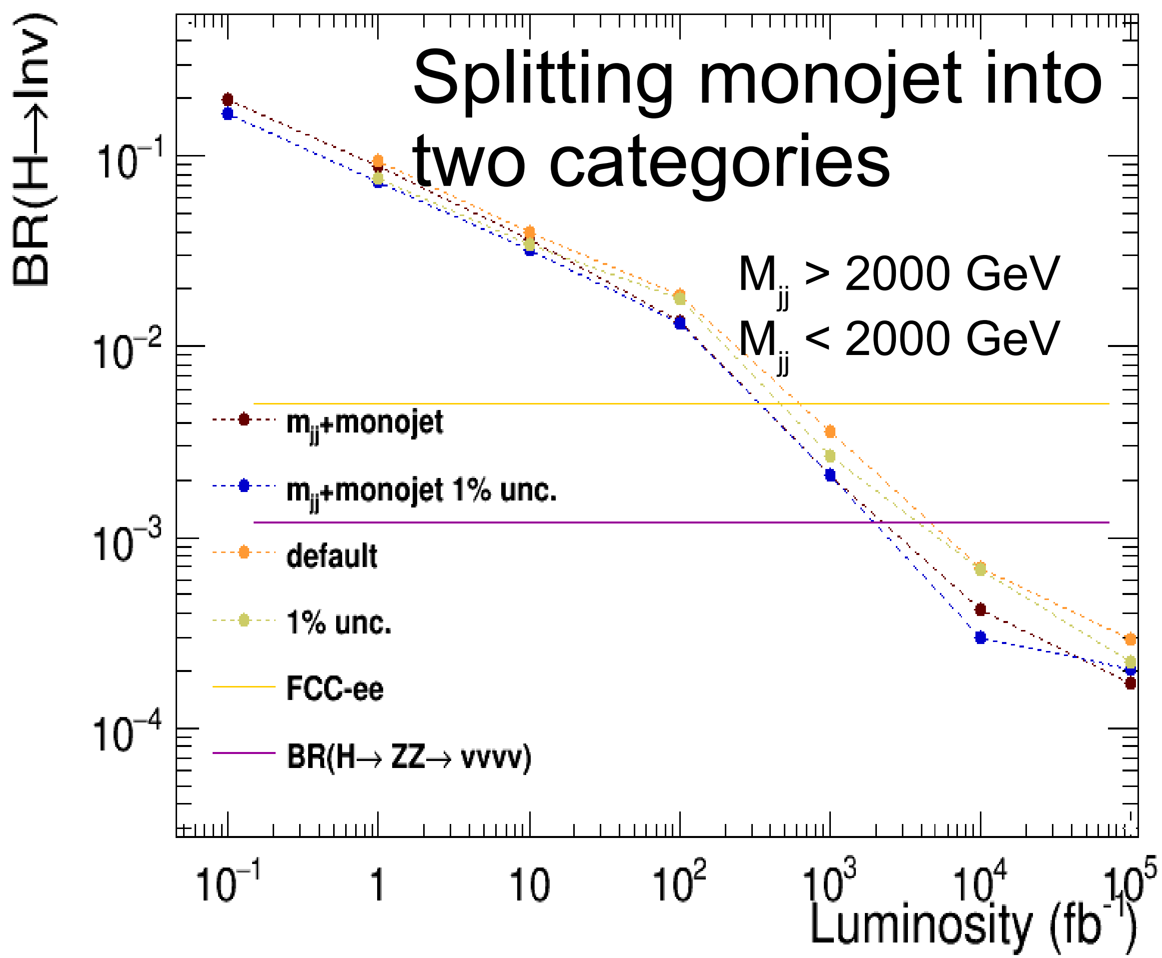


At high mjj purity for VBF can become quite high

Can we extend things?

- Can consider targetting the VBF final state?





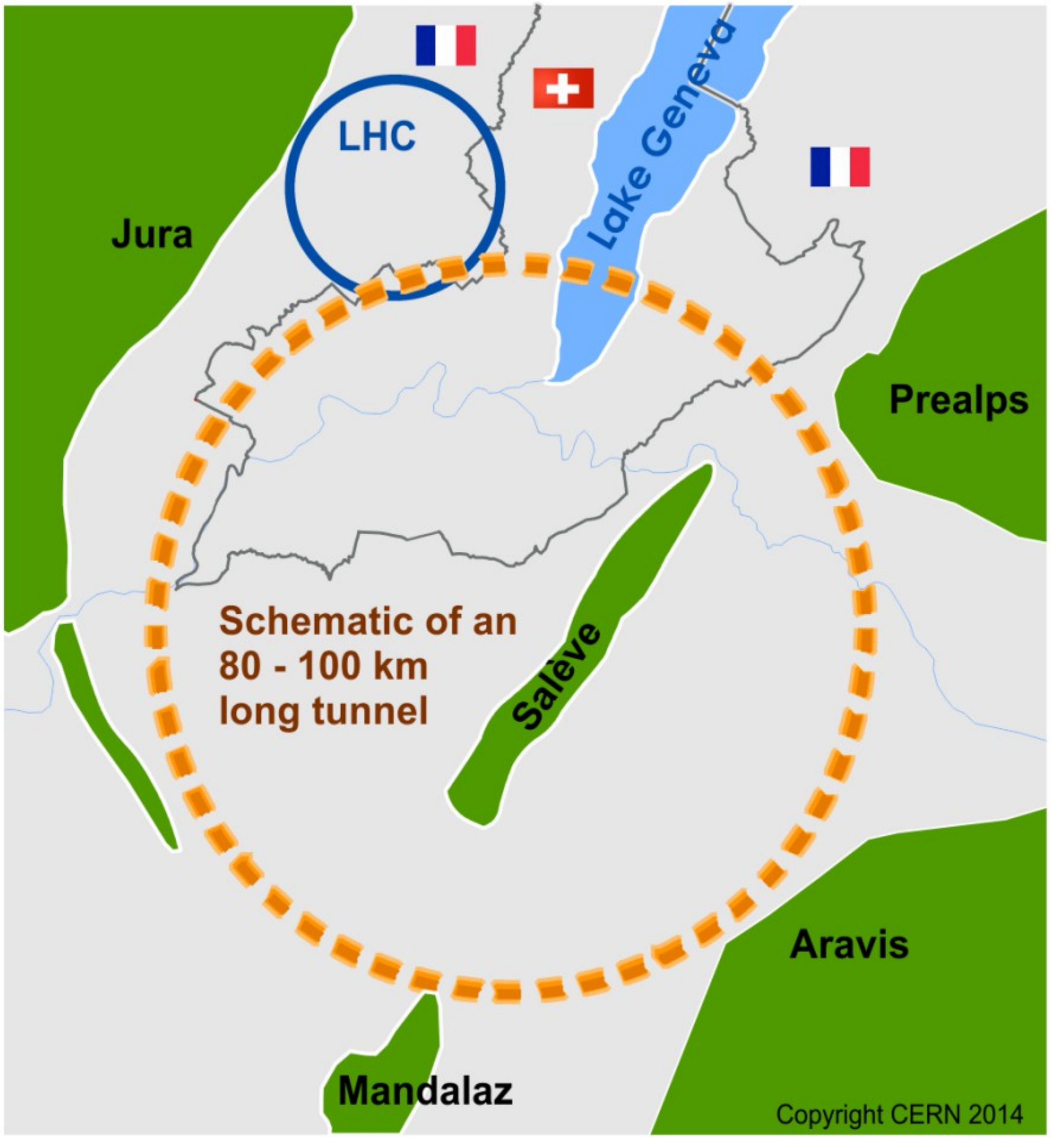
Note the broad sensitive region

The 100 TeV collider*

*Same ring is being considered for e^+e^- collider (its not relevant for DM)

What is the 100 TeV collider?

- A new and very large ring



16T magnets
(LHC 8T)
New cables NiSn($$)
LHC uses NiT (MRI)

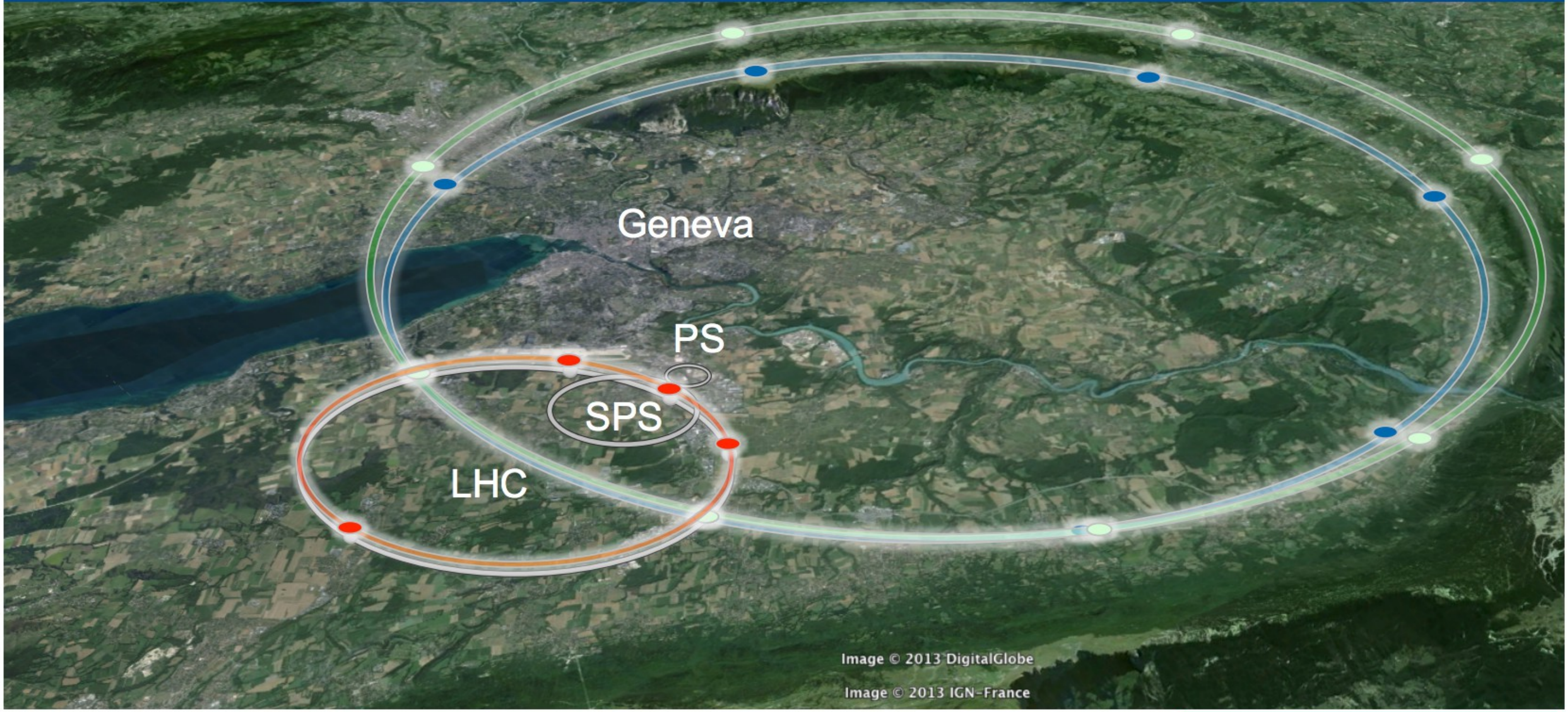
Ring size :
14 TeV→50 TeV

Magnet:
50 TeV→100 TeV

Alternative (just magnet)
14 TeV→28 TeV

Another Perspective

FCC-hh integration and options



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

The competition

CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042

Specs

Hadron collider FCC-hh parameters

Energy	**100 TeV c.m.**
Circumference	**~ 100 km (baseline) [80 km option]**
Dipole field (50 TeV)	**~ 16 T (baseline) [20 T option]**
Dipole field (3 TeV inject.)	**~ 1 T (baseline) [1.2 T option]**

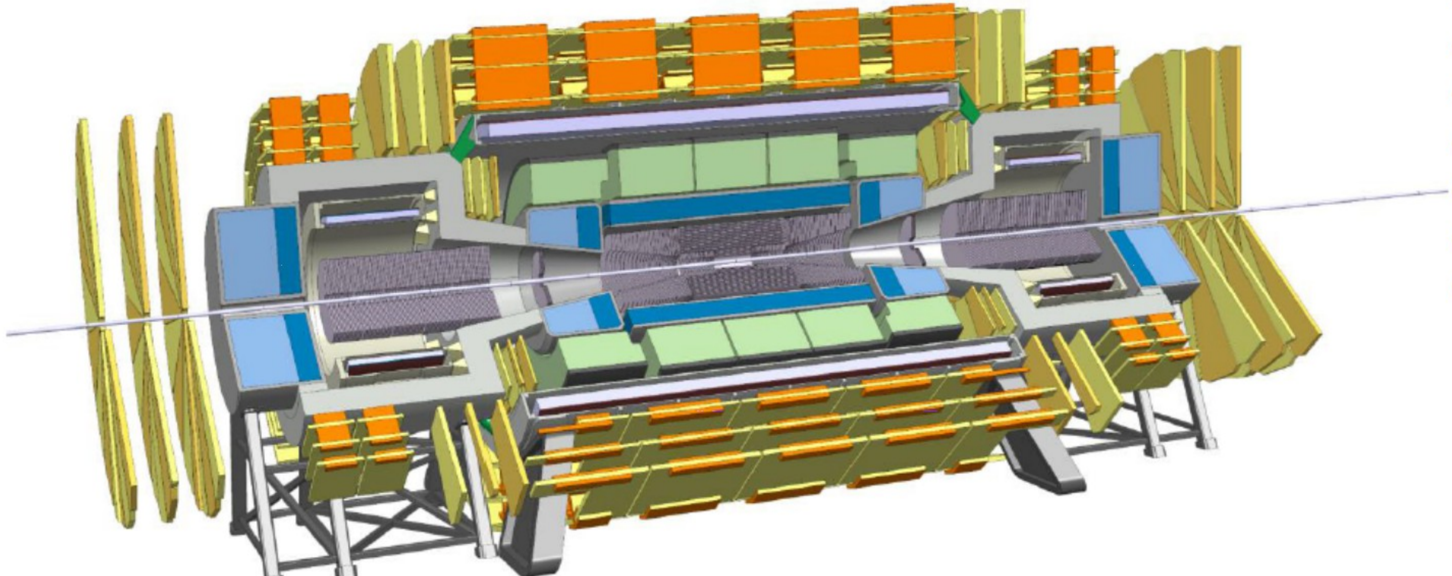
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	1×10^{11} p
Emittance normalised	2.15×10^{-6}m, normal.
#bunches	10500
Stored beam energy	**8.2 GJ/beam**

Available from SPS/ LHC today
→3 TeV injector baseline for FCC-hh

300-1000 PU

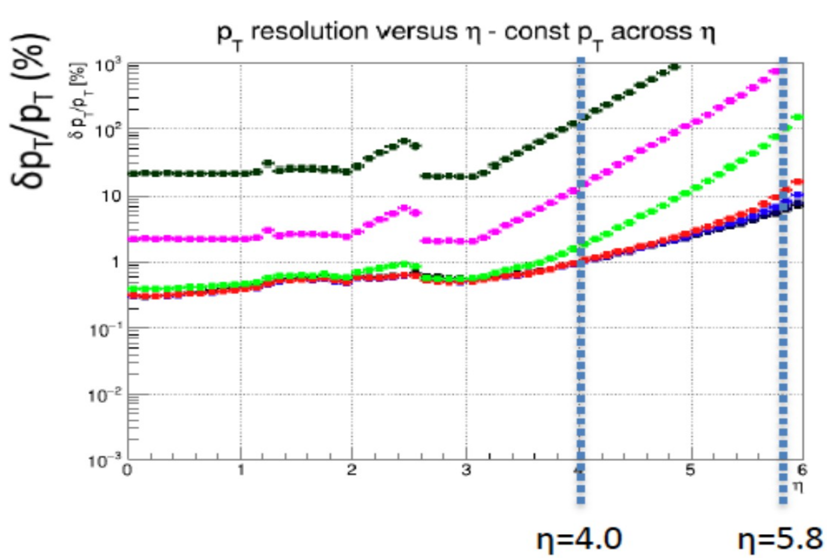
# Interaction Points	2 main experiments
β*	1.1 m [baseline]
Luminosity	**5×10^{34} cm^{-2}s^{-1}** [baseline]
Synchroton radiation arc	**~30 W/m/aperture (fill. fact. ~78% in arc)**

Reference detector for the CDR



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

Concept: a giant CMS with extended η coverage



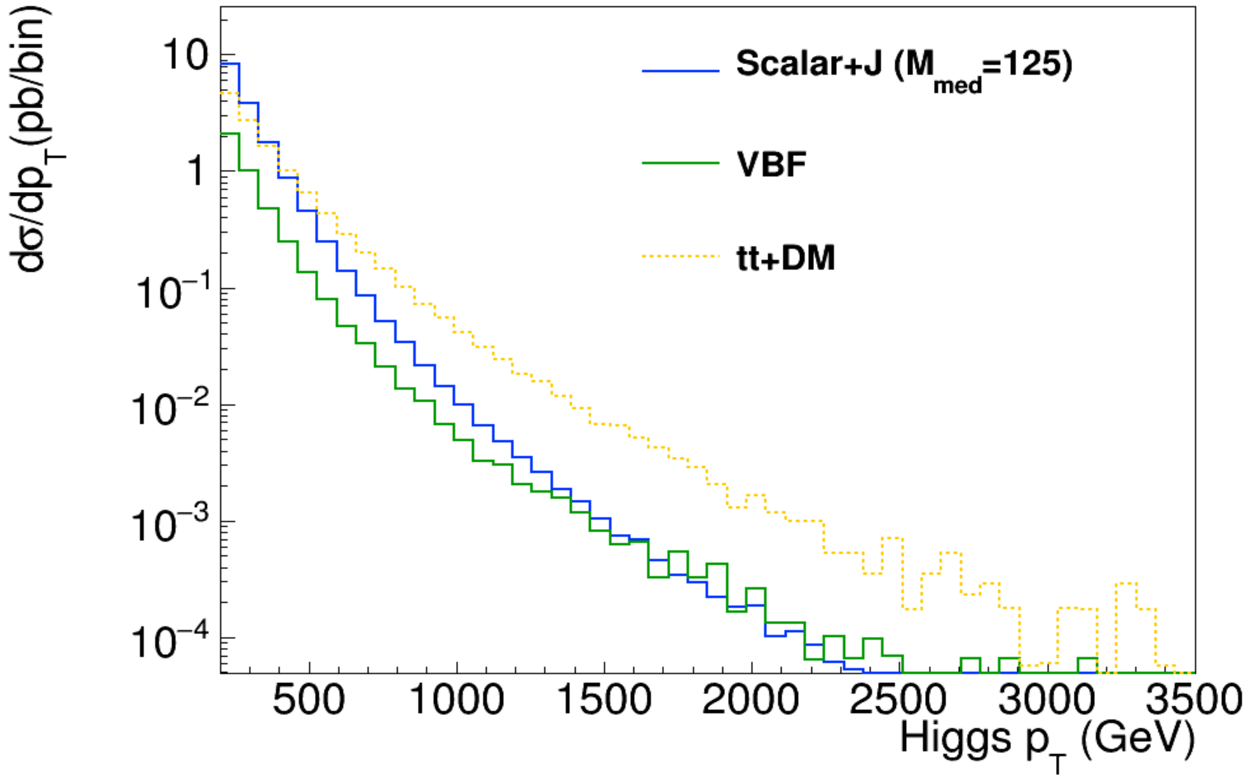
p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

What about the cross sections?

- The relative rate to all processes is similar
  - σ(100 TeV/14 TeV) : ggH : 14.7
  - σ(100 TeV/14 TeV) : VBF : 18.6
  - σ(100 TeV/14 TeV) : WH : 9.8
  - σ(100 TeV/14 TeV) : ZH : 12.5
  - σ(100 TeV/14 TeV) : ttH : 60.8
  - σ(100 TeV/14 TeV) : bbH : 14.8
  - σ(100 TeV/14 TeV) : HH : 42.0
  - Except for ttH
- Means we expect VBF to give similar improvement
- Benchmarking agains ggH means ttH/VBF have a lot of room to gain

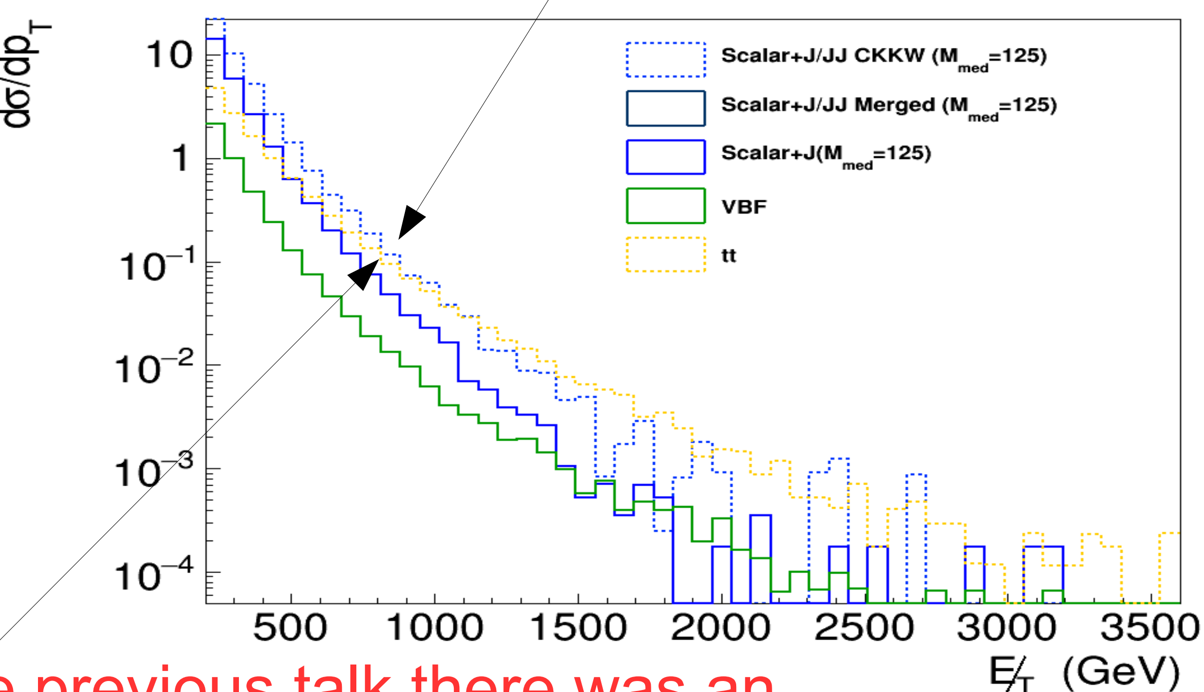
What are the production modes?

- At 100 TeV :
  - ttH is hugely enhanced
  - When compared with H+1j form gluon fusion it wins



What are the production modes?

- At 100 TeV :
  - ttH is hugely enhanced
  - When compared with H+1j form gluon fusion it wins
  - However H+2j is also large



Note in the previous talk there was an issue in the 2jet generation (was a bug)

Cross checking the 2jet model

- When this was previously present
  - There was a bug (turns out the impact is small!)
- At 100 TeV :
  - Different setups give roughly the same yield